Use of Agricultural Waste Fibres as Enhancement of Soil Blocks for Low-Cost Housing in Ghana

By

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DECLARATION

I declare that the work presented in this *thesis* is, to the best of my knowledge and belief, original except as acknowledged in the text. The work was carried out in accordance with the regulations of the University of Portsmouth and the material has not been submitted, in part or in whole, for any other degree at this or any other university.

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ABSTRACT

The work presented in this thesis investigates the properties and internal mechanism of novel soil blocks made with three different agricultural waste fibres in two different soil types. Experiments were conducted and the main variables include: three fibres (bagasse, coconut and oil palm), three soil samples (Brown, Red and Horsea Island), five fibre content (0, 0.25, 0.5, 0.75 and 1 wt.%) and five fibre aspect ratios (25, 50, 75, 100 and 125). Tests conducted include density, compressive, tensile, erosion, wearing, SEM, CT scan, optical microscope analysis and pull-out.

Initial tests on small cylindrical specimens produced to determine the effect of compaction rate for producing soil blocks on the strength properties found that, although the low rate of compaction achieved slightly better performance characteristics, there was not a statistically significant difference between the soil blocks produced with low and high compaction rates.

Investigation on the effect of aspect ratio of the fibres on the mechanical properties of soil blocks revealed that, in general, an increase in fibre aspect ratio has a positive effect (20-25% improvement) on the strength of enhanced soil blocks. Fibre lengths of 50, 80 and 38 mm for coconut, bagasse and oil palm fibres, respectively, produced maximum strength, only bagasse showed an optimum. Another investigation on the properties of soil blocks reinforced with different fibre contents found that, the inclusion of fibres, enhanced the properties of soil blocks (16-57% strength and 20-70% durability improvement), with optimum performance generally at 0.5wt.% fibre content. Furthermore, the high clayey soil performed better in all the properties of the fibre reinforced soil blocks than the low clay soil.

The study on the internal mechanism of fibre-soil matrix interaction established that fibres in the soil matrix are randomly distributed with gaps between the fibres and matrix due to fibre shrinkage. It also found that natural fibres in soil matrix can either be pulled out or break under load. In addition, fibres in the soil matrix undergo changes in size when wet and at its natural moisture content state. In general, the work concludes that the fibre reinforced soil blocks are suitable for use as a building material especially for less economically developed (LED) countries, particularly Ghana, because of the abundance and low-cost of the selected fibres.

DEDICATION

I dedicate this Thesis to my wife (Mavis Amponsah Boaffoh) and children (Erica Danso, Prince Danso and Samuel Danso) for their love, prayers, support, sacrifice and patience during the period of my study.

The Thesis is also dedicated to my parents (Sam Danso and Vincentia Densu) as well as my siblings (Eric Doku, Henry Danso, Harry Danso and Gifty Animah Danso) for their prayers and support.

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LIST OF ABBREVIATIONS

AECT	Advanced Earthen Construction Technologies
ADO	Adobe
ASTM	American Society for Testing Materials
ASCE	American Society of Civil Engineers
AR	Aspect Ratio
BS	British Standard
BS EN	European Standard adopted by British Standards Institution
CEB	Compressed Earth Block
CID	Construction Industries Division
CIWMB	California Integrated Waste Management Board
CIP	Concrete in Practice
DIN	Deutsches Institut für Normung (German Institute for Standardization)
FRC	Fibre Reinforced Concrete
GHG	Green House Gases
ISD	Indicators of Sustainable Development
ISO	International Standard Organization
LED	Less Economically Developed
LEDCs	Less Economically Developed Countries
LL	Liquid Limit
MDGs	Millennium Development Goals
NZS	New Zealand Standard
PI	Plasticity Index
PL	Plastic Limit
PC	Portland Cement
PSD	Particle Size Distribution
RE	Rammed Earth
SDGs	Sustainable Development Goals
SSA	Sub-Sahara Africa
USA	United States of America
US	Unsuitable Soil
UN	United Nations
UNEP	United Nations Environment Programme

LIST OF EQUATIONS

NOMENCLATURE

ρ	Bulk density of soil	kg/m^3
ρ_d	Dry density of soil	kg/m^3
Ip	Plasticity index of soil	%
γ	Specific weight of fibre	g/cm^3
E	Modulus of elasticity	
fc	Compressive strength	N/mm^2 (MPa)
ft	Tensile strength	N/mm^2 (MPa)
Cw,s	Coefficient of water absorption by capillary	kg/(m^2×min|)
LS	Linear shrinkage	%
F_{bond}	First maximum force of fibre	N
σ_{uts}	Breaking strength	MPa
D_f	Mean fibre diameter in specimen	mm
w_L	Liquid limit of soil	%
w_p	Plastic limit of soil	%
Ip	Plasticity index of soil	%
σ_{uts}	Breaking strength of fibre	MPa
l_r	Fibre length in soil matrix at the point of rupture	mm

LIST OF APPENDICES

DISSEMINATION

Publications

Danso, H., Martinson, B., Ali, M. & Williams, J. (2015). Effect of fibre aspect ratio on mechanical properties of soil building blocks. *Construction and Building Materials, 83*, 314-319, doi:10.1016/j.conbuildmat.2015.03.039

Danso, H., Martinson, B., Ali, M. & Mant, C. (2015). Performance characteristics of enhanced soil blocks: a quantitative review. *Building Research & Information*, 43(2), 253-262. DOI:10.1080/09613218.2014.933293.http://www.tandfonline.com/doi/pdf/10.1080/09613218.2014.933293

Danso, H., Martinson, B., Ali, M. & Williams, J. B. (2015). Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres. *Construction and Building Materials, 101, 797–809,* http://dx.doi.org/10.1016/j.conbuildmat.2015.10.069

Danso, H., Martinson, B., Ali, M. & Williams, J. B. (2015). Effect of sugarcane bagasse fibre on the strength properties of soil blocks. 1st International Conference on Bio-based Building Materials. June 22-24, Clermont-Ferrand, France. 251-256

Focused group workshop

Focus group workshop training has been organised for masons in Ghana who are directly involved in supervising and constructing earthen structures, on the benefits and techniques of producing the fibre enhanced soil blocks. Details can be found in Section 10.4.

Distribution of technical guide

A technical guide on the benefits and production of agricultural waste fibre reinforced soil blocks was prepared and distributed to the beneficiaries of the study in Ghana. Details can be found in Section 10.4.

Prizes won at University of Portsmouth

1. Best poster – 2015 Graduate School Poster Competition
2. Best poster – 2015 Faculty of Technology Research Conference
3. Second best paper – 2015 Faculty of Technology Research Conference
4. Poster Runner up – 2013 Faculty of Technology Research Conference

PART I

INTRODUCTION

CHAPTER 1

1. INTRODUCTION

1.1 INTRODUCTION

This chapter presents the context, the focus and the structure of the study. It consists of the background of the research, problem statement, the aim and objectives of the research, significance of the research and the structure of the thesis.

1.2 BACKGROUND OF THE RESEARCH

This section of the chapter discusses the background issues concerning the provision of low-cost housing with the use of fibre reinforced soil blocks. It consists of the need for producing low-cost housing, the use of soil/earth for producing low-cost housing, the concept of enhanced soil blocks, problems associated with soil/earth for building houses and the use of agricultural waste as building material.

1.2.1 The need for producing low-cost housing

Since the early 1950s, considerable attention has been focused on the importance of access to low-cost housing for low income populations, through researching into building materials and techniques that use locally available and abundant resources (Rigassi, 1985). More recently the consideration of social and cultural aspects of design and construction techniques have also received attention. The gradual reduction of imports of conventional building materials and the development of techniques which meet the needs of end-users whilst taking account of their economic abilities is of great importance.

The United Nations (UN Habitat, 2005) and Sori (2012) estimate that about 60% of the population of Africa resides in slums and informal settlements. As of 2007, the World Bank identified about 152 less economically developed countries (LEDCs) in which one-third of the people are without adequate housing. There is no evidence presently of any significant improvement of this situation. This situation is primarily caused by rapid growth of urbanisation and increase in population, particularly in Sub-Sahara Africa (SSA) without corresponding housing infrastructure (Sori, 2012). In view of this, the United Nations is using various interventions to improve the statistics by encouraging the use of sustainable construction materials and appropriate technologies (UN Habitat, 2008). This ties in with the Millennium Development Goal 7D (MDG 7D) which aims at making improvement in the lives of 100 million people who live in slum areas by 2020, and also Target 11.1 of Sustainable Development Goals (SDGs) which aims at ensuring access for all to adequate, safe and affordable housing as well as basic services and upgrade slums by 2030. The growth in the construction industry has led to an increased demand for construction materials that exceed the production capacity in most African countries (Zami and Lee, 2011). The need for providing adequate housing therefore requires research and continued investment in appropriate technologies that ensures low cost of construction materials and minimises environmental impact (UN Habitat, 2009).

Lack of housing globally is seen in both rural and urban areas with proliferation of informal settlements which usually cause environmental pollution with little or no access to garbage disposal and sanitation (United Nations Environment Programme) (UNEP, 2002). The increasing demand for housing, coupled with informal settlements constantly expanding as well as low-income household’s inability to afford decent housing, are underlined by the crucial necessity to research into new methods of design and material technologies.

The choice of sustainable construction materials and design to produce low-cost housing can be helpful to address not only economic and social issues but also environmental issues such as reduction in greenhouse gas (GHG) emissions. According to Al-Sakkaf (2009) there is the need to construct houses that are durable and also at low-cost. It can therefore, be reasoned that producing low-cost housing will enable those in low-income bracket to acquire decent houses to live, reduce the environmental impact of construction activities and reduce the housing deficits especially in the LEDCs. According to Khatib (2009) construction professionals, researchers and academics have a major role to play in sustaining our environment, through efficient utilisation of natural resources.

1.2.2 Soil/earth for producing low-cost housing

Soil has widely been used for building houses for thousands of years and is still an important material and has future applications, especially for construction of low-cost housing. Affordable construction and building materials are essential for the development of low-cost housing. Soil bricks and blocks are an attractive building material because they are inexpensive to produce (Ismail and Yaacob, 2011). Earth is affordable, environmentally friendly and abundantly available. The use of earth for the production of bricks and blocks for building houses has existed in many countries for a very long time (Binici et al., 2005). Earth is perhaps the most accessible and economical natural material for making bricks and blocks (Chan, 2011). Until now, the development of engineering materials is yet to render earth obsolete as a construction material, especially in low income places such as SSA (Olotuah, 2002).

Earth has the advantage of being recycled, therefore bricks and blocks produced with soil can return to the earth without polluting it and can be used again (Rigassi, 1985). Furthermore, the energy requirement for producing soil bricks and blocks is relatively low of about 5 kWh/m^3 as compared to about 1000 kWh/m^3 required for burnt bricks and blocks, and about 400-500 kWh/m^3 for concrete production (Al-Sakkaf, 2009).

Earth has the advantage of being used for variety of building components such as walls, roofs and floors. It has good thermal properties which help in regulating internal room temperature. Most importantly, it can be used to produce low-cost housing due to its abundant availability and inexpensiveness in most countries (Morris and Booysen, 2005).

1.2.3 Enhanced soil blocks

Soil or earth is one of the ancient building materials that continue to gain attention in the present built and environment industry worldwide. Stabilisation, reinforcement or enhancement of soil seeks to increase the engineering properties of the blocks for the purpose of constructing robust and resilient houses. Stabilised or enhanced soil blocks are sun dried blocks made from a homogeneous mixture of soil and any stabiliser for the purpose of improving the strength properties (Vilane, 2010). Soil can be enhanced or stabilised by compaction and introduction of additives (Bahar et al., 2004). The technique of using fibres to reinforced soil blocks increase the blocks' mechanical strength (Maher and Ho, 1994). Enhanced soil blocks are therefore blocks that are made with soil, fibre and/or binder, water, compacted and sun-dried (unfired) to improve their engineering properties.

1.2.4 Why the use of soil for building houses

Houses built with soil help in promoting sustainable management of natural resources. Building houses with soil contributes less to environmental pollution, have low energy cost and low initial and lifetime construction costs. Even though building houses with soil is time consuming, its cost benefit analysis makes it preferable especially for those within the low income bracket.

The construction industry generates a very high percentage of environmental impact from its processes particularly in the developed countries (UNEP, 2003). The construction industry in Europe is responsible for about 40% of the overall environmental burden (UNEP, 2003). This implies that using soil/earth for producing houses will not only be economically beneficial to the users of the houses but also the environment affecting almost everyone in the world.

1.2.5 Problems of constructing houses with soil/earth

One of the problems associated with earth as a construction material is the issue of low durability and strength properties (Venkatarama Reddy and Prasanna, 2009, Heathcote, 1995, Guettala et al., 2002, Guettala et al., 2006). Soil in its natural state lacks the dimensional stability required for building houses (Riza et al., 2011).

Another problem of using soil as a building material is its wearing or erosion characteristics when exposed to rain. Insects/rodents can also make holes in floors and walls of houses constructed with earth. Other issues include labour intensive in their construction, structural limitations, regular maintenance, special skills needed for plastering and required wide wall thickness. There are also the problems of cracking and shrinkage with the use of earth for building houses (Bahar et al., 2004).

This means there is the need to stabilise, reinforce or enhance the raw soil/earth with some materials in order to increase their strength and durability properties for construction purposes. One of the ways of reinforcing soil for improve performance is the use of agricultural waste fibres.

1.2.6 Agricultural waste as building material

There is a large waste generated by agriculture in most countries from harvesting and post harvesting operations. These wastes are usually burned or dumped into landfills which contribute to increase in GHG emissions and pollute water. The main concern is the increase in carbon dioxide (CO_2) released by the burning around the world (Zami and Lee, 2009). The improper storage and leaking of the agricultural wastes can also contribute to GHG emission (EEA, 2006). These wastes can be incorporated in building materials for improving their engineering properties. Several agricultural wastes like straw and leaves from crops, fibres from fruits, husks and stalks as well as shells contain fibrous content which could be used as ingredient in composite building materials (Rowell et al., 1996, Chan, 2011).

Therefore there is the need for research to investigate how to use these wastes to the benefit of people and not to their disadvantage. It is therefore appropriate to research in turning agricultural wastes to the benefits of mankind such as using them as building materials.

1.3 PROBLEM STATEMENT

Conventional construction and building materials such as steel, cement, concrete, sandcrete blocks, burnt bricks and tiles require the extraction of large quantities of raw materials, causing depletion of natural resources and environmental damage. The manufacturing process of these materials is energy intensive, releasing CO_2 and other pollutants into the atmosphere. These emissions contaminate water, air, soil, flora, fauna and aquatic life as well as affecting human health (Safiuddin et al., 2010). In addition, the cost of conventional building materials keeps increasing because of the energy required for the production, increasing scarcity of natural resources and high transportation cost from the factories to the construction site. These environmental and economic concerns have generated interest in research into alternate building materials, such as soil building blocks and construction techniques that are more sustainable.

Enhancement of the engineering properties of soil blocks with agricultural waste fibres has attracted the interest of many researchers in the past decade. Fibres such as chopped barley straw, processed waste tea, vegetal, oil palm empty fruit bunches, lechuguilla natural fibres, pineapple leaves and oil palm fruit bunch, cassava peel, *Hibiscus Cannabinus* and straw have been used as stabilisers to enhance the properties of soil blocks/bricks by Bouhicha et al. (2005), Demir (2006), Achenza and Fenu (2006), Kolop et al. (2010), Juárez et al. (2010), Chan (2011), Villamizar et al. (2012), Millogo et al. (2014) and Parisi et al. (2015), respectively. All these studies showed improvement in the engineering properties of the stabilised soil blocks/bricks over the unstabilised. This makes agricultural waste fibres important stabilising material for soil blocks. Besides the structural benefits, they also have economic, environmental and social significance when used to stabilise soil blocks for earthen construction.

The energy requirement and the processes involved in manufacturing soil blocks are much lower compared to cement, sandcrete blocks and burnt bricks production (Alavéz-Ramírez et al., 2012, Al-Sakkaf, 2009, Deboucha and Hashim, 2011, Ismail and Yaacob, 2011). Soil is locally available and abundant which makes it easy and affordable to obtain (Chan, 2011), therefore, people in the low-income bracket can afford to acquire their own houses using soil blocks. Furthermore, instead of burning the agricultural wastes which contribute to high carbon emission and pollute the environment, these wastes can be used to produce enhanced soil blocks.

The importance of agricultural waste fibres is in their availability in many economies, since most countries have significant agricultural activity (Kriker et al., 2008). Different agricultural wastes can be found in different countries depending on the type of crops available. For example, there are abundant wastes generated in Ghana from coconut husk, sugarcane residue (bagasse) and oil palm fruit residue. Different agricultural wastes have therefore been used to enhance the properties of soil blocks in different countries. Studies on the possible use of other agricultural wastes to enhance the properties of soil blocks will add to knowledge and extend the debate on the utilisation of waste in soil matrix. There is therefore the need to investigate the use of sugarcane bagasse fibres, oil palm fruit fibres and coconut husk fibres as enhancement of the properties of soil blocks.

When considering the inclusion of fibres in soil blocks, two important factors contribute to strength development. These factors are fibre content (the fraction of fibre to the soil) and the fibre aspect ratio (the ratio of length to diameter of the fibre in the soil). Most studies on the use of agricultural waste fibres for enhancement of soil blocks focused on the fibre content, with few incorporating fibre lengths in their studies (Aymerich et al., 2012, Bouhicha et al., 2005, Gaw and Zamora, 2011, Juárez et al., 2010). However, it is not only the fibre length that is critical for strength development but also the fibre diameter. Fibre aspect ratio is the ratio of length to diameter of a fibre (or the length to diameter relationship of fibre). There is also the need to determine the aspect ratio of fibres that will produce the peak strength to be used for stabilising soil blocks.

While widely used informally, the technique of fibre-soil composite has not been fully embraced by the formal building sector due to lack of information on the interaction between fibre and soil matrix (Diambra et al., 2013). The benefit of fibre reinforcement comes from fibre-soil interaction, and insight into the internal mechanism of the interaction between fibre and soil is therefore of importance to improve design processes and for wider acceptance of the material in the formal construction industry. There is therefore the need also to investigate the internal mechanism of soil matrix reinforced with natural fibres, in order to determine the distribution of the fibres in the matrix, any existence of gaps at the peripheral of the fibres in the matrix, any effect of fibres pull-out on the composite and the interfacial shear strength of the fibre-soil composite.

1.4 AIM AND OBJECTIVES

The aim of this research is to investigate the properties and internal mechanism of soil blocks enhanced with agricultural waste fibres for producing low-cost housing in a developing country context with particular reference to Ghana.

To achieve this aim, the following objectives are pursued:

- To determine the properties of soil to be used for making enhanced blocks.

- To determine the characteristics of agricultural waste fibres (coconut husk, oil palm and bagasse) to be used as enhancement in soil blocks.
- To investigate the fibre aspect ratio that will produce optimum mechanical strength of the enhanced soil blocks.
- To investigate the physical, mechanical and durability properties of soil blocks enhanced with different agricultural waste fibre content.
- To study the internal mechanism of the soil blocks enhanced with agricultural waste fibres.
- To disseminate the enhance soil blocks research findings so that the work is uptaken by beneficiaries/end users.

1.5 SIGNIFICANCE OF THE STUDY

This research will contribute to knowledge and provide significant benefits to the academics, practitioners, governments of developing countries and the end-users of soil blocks. The outcomes of this study have structural, economic, environmental and social benefits.

1.5.1 Structural

Structural significance is the improved strength and durability properties that the study will investigate. The inclusion of agricultural waste fibres in soil blocks will therefore improve especially the compressive and tensile strength properties and provide resistance to erosion which is caused by rain. The low tensile strength and erosion of soil blocks have been identified as setbacks to earth structures.

1.5.2 Economic

Economic significance is concerned with the technique as well as the materials that are required for making the blocks which provide low-cost and affordable housing. Affordable housing is one of the major concerns of every government and the citizens. One must therefore consider the effect of this on the local economy. These effects are reflected in the reduction of imports of raw materials for producing cement which is used for making sandcrete blocks as well as the transportation to remote areas. The inclusion of fibres in the soil blocks will eliminate the over-reliance on cement for use in walling which will reduce the cost of housing. This will help governments and private developers to produce more houses that will be affordable.

Reduced energy consumption is also important. This is evident in the production of the materials, the soil blocks consume much less energy as compared with sandcrete and burnt bricks. Again, the energy required to keep the room temperature at the desirable comfort (eg. air-conditioning, fanning and heating) is less for houses constructed with soil blocks. Furthermore, soil is locally available and abundant which makes it easy and affordable to obtaine, therefore, people in the low-income bracket can afford to acquire their own houses using enhanced soil blocks.

1.5.3 Environmental

The construction industry is a major source of CO_2 emission, and therefore the use of earth and agricultural waste fibres can reduce the impact of construction on the environment. This is because the process involved in manufacturing soil blocks has little effect on the environment as compare to cement and sandcrete blocks production. In addition, instead of burning agricultural waste which contributes to high carbon emission and pollutes the environment, these wastes will be used to produce enhanced soil blocks. This means the outcome of this study provides numerous environmental benefits, including reduction of CO_2 emission and environmental pollution.

1.5.4 Social

Socially, soil/earth construction meet the requirements of the local production situations such as using local existing or easily transferable skills, avoiding costly training of workforce, reducing displacement of labour and reducing societal or cultural disruption. Using enhanced soil blocks for housing enables the traditional people to incorporate in the design of houses their cultural values and symbols and beliefs in order to preserve their cultural heritage. Traditional houses reflect cultural heritage of people and also encapsulate traditional norms and values.

Earth construction requires less skills training and promotes construction of houses on self-help basis. The results of the study will help promote the adoption of earth construction by practitioners and outline the process involved in producing the enhanced soil blocks.

1.6 STRUCTURE OF THE THESIS

This section outlines the body (organisation) of the thesis by providing the path that the whole research work follows. The thesis consists of five (5) main parts with twelve (12) chapters, including references and appendices. These parts and chapters are arranged and presented in Table 1.1.

Table 1.1. Thesis structure

PART I	INTRODUCTION	
	Chapter 1	Introduction
PART II	LITERATURE REVIEW	
	Chapter 2	Conceptual review
	Chapter 3	Quantitative review
PART III	EXPERIMENTAL WORKS	
	Chapter 4	Properties of experimental soils
	Chapter 5	Properties of experimental fibres
	Chapter 6	Pre-test laboratory works
	Chapter 7	Fibre aspect ratio effect on strength of soil blocks
	Chapter 8	Properties of enhanced soil blocks with fibre content
	Chapter 9	Internal mechanism of fibre-soil composite
	Chapter 10	Overview discussion
PART IV	IMPACT DISSEMINATION	
	Chapter 11	Impact dissemination of the research findings
PART V	CONCLUSION	
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Chapter 1 introduces the background, problem statement, significance and the structure of the thesis. Chapter 2 reviews literature which conceptualises the framework of the research. Chapter 3 is the second part of the literature review, which seeks to empirically survey the volume of research works conducted in the stabilisation or enhancement of soil blocks. Chapter 4 determines the properties of the soil types that are to be used in the study. The properties of the agricultural waste fibres that used in the study are determined in chapter 5.

Chapter 6 investigates the effect of compaction rate on the properties of soil blocks, which is a preliminary laboratory work before the main field work.

The investigation on the fibres aspect ratio on the mechanical properties of the fibre reinforced soil bocks is reported in Chapters 7. While Chapter 8 reports the investigation on the physical, mechanical and durability properties of the soil blocks reinforced with different fibre contents. Chapter 9 investigates the internal mechanism of fibre and soil matrix as a composite material. The properties of the fibre enhanced soil blocks were discussed and the explanation behind the observations provided with connections made between the observations. The findings of the fibre reinforced soil blocks impact dissemination are in chapter 11. The final Chapter (Chapter 12) contains the conclusions of the study and makes recommendations to practitioners and academics for further works.

All citations in the thesis are listed in the list of references for easy access and location, which is followed by other important and supporting document and information in the form of appendices.

1.7 SUMMARY

This chapter of the research introduced the background, the focus and the structure of the study. It consisted of the background of the research, problem statement, the aim and objectives of the research, significance of the research and the structure of the thesis. The background of the study placed the study in focus and outlined the general context in which the research is underpinned. The problem statement set out the circumstances surrounding the research and the need that motivated the research. The aim of this research was to contribute to the general body of knowledge and research work in the field of civil engineering, precisely in the area of construction and building materials, by highlighting the volume of research work undertaken in the stabilised or enhanced soil blocks and investigate the physical, mechanical and durability properties of laboratory based soil blocks enhanced with agricultural waste fibres. The significance of the research was explained in fourfold: structural, economic, environmental and social. Finally, the structure of the thesis outlined the body of the research by providing the path that the whole research work followed. The write up consists of 5 main parts with 11 chapters.

PART II

LITERATURE REVIEW

CHAPTER 2

2 CONCEPTUAL REVIEW

2.1 INTRODUCTION

This part of the study reviews the main concepts of stabilisation of earthen construction for low-cost housing. The main concepts include earth construction, low-cost housing, the issues with building materials in Africa, earth/soil as a building material and agricultural waste fibres as building materials.

2.2 EARTH CONSTRUCTION

This sub-section of the study discusses the construction of earth houses. It highlights the main concepts of earth construction such as the techniques for earth construction and stabilisation techniques.

2.2.1 Techniques for earth construction

Earth-based construction and building have existed for thousands of years and are still practiced today. Important advantages, such as low-cost of construction and less harm to the environment, make these techniques attractive. Five basic techniques of earth construction are rammed earth, compressed earth blocks, adobe blocks, cob buildings, and wattle and daub.

2.2.1.1 Rammed Earth

Rammed Earth (RE) has different names such as taipa (in Portuguese), tapial (in Spanish) and pise/de terre (in French). RE is one of the earth construction techniques that creates dynamically compacting soil between temporary forms to make a monolithic wall (Hall and Djerbib, 2004). The thickness of the wall is usually between 300 and 600 mm.

The RE construction process involves placing layers of wet mixed soil within formwork, similar to that found in concrete construction (Figure 2.1). Each layer is then compacted on top of the previous layer using a pneumatic rammer before the formwork is removed, revealing a continuous load-bearing wall (Smith and Augarde, 2012). The wet RE is then left to dry naturally and reaches full strength once the entirety of the wall has dried to the ambient conditions (Walker et al., 2005).

Figure 2.1: Rammed earth
(Bühler, 2008)

To ensure that the layers stay together, treatment of the top surface before adding subsequent layer is important. Some of the treatments such as brushing off loose material, notching surface and moistening surface improve the bond between the layers (Maniatidis and Walker, 2003).

2.2.1.2 Compressed earth block

Compressed earth block (CEB) is earth construction technique which soil/earth block is made by mechanically pressing soil particles into a mould. The difference in CEB from RE is that the latter uses a larger formwork into which the soil is poured and compacted to form a whole wall. The CEB (Figure 2.2) are made in small sizes (blocks) and installed onto the wall by hand with mortar, which is spread very thinly between the blocks for bonding. The reason for compacting soil/earth in a mould is to improve the engineering properties of the material (Rigassi, 1985).

CEB became popular in South America in 1950s when Cinva Ram was made by Raul Ramirez in Bogota, Colombia (Guillaud et al., 1995). The Cinva Ram is a manually pressed machine which is operated in a lever action to make compressed earth blocks. Lately, electrically powered machines have been developed by companies such as Hydroform.

Figure 2.2: Compressed earth blocks
(Arumala et al., 2004)

2.2.1.3 *Adobe block*

Adobe block is a block which is usually made with clayey soil and organic matter such as straw or dung (Wu et al., 2013). The soil usually consist of clay, silt, sand and gravel. The organic material is used as a binder and sometimes prevent shrinkage crack development in the block (Garrison, 2013). The dung (usually cow dung) offers the same advantage as the organic material and also has the advantage of deterring insect attack.

The adobe blocks (Figure 2.3) are made in forms in which the mixture of the soil and the organic material is poured, manually tamped and the form removed after setting and allowed to dry in the sun. Earth construction made with adobe blocks are common in South America, Africa, Eastern Europe and Asia.

Figure 2.3: Adobe blocks
(Varga, 2009)

2.2.1.4 Cob

Cob is one of the ancient earth construction technique which consists of earth and straw similar to adobe. It has been used for construction since prehistoric times. Cob is one of the earth construction techniques that were used for the oldest man-made structures in Afghanistan (McArdle, 2011). According to Hill (1996) cob technique was used in the Maghreb and al-Andalus in the 11 to 12th centuries. Cob is also popular in England which is alternatively called 'clom' in Wales and 'mudwall' in Scotland (Little and Morton, 2001).

Basically, the cob (Figure 2.4) procedure involves stacking earth balls on top of one another and lightly compact them with hand or feet to form a monolithic walls (Houben and Guillaud, 1994). The compaction of cob walls is usually done by the feet of the operatives or the use of some of their tools such as spade or planks (Forster et al., 2008).

Figure 2.4: Cob structure
(Kim-Carberry, 2011)

2.2.1.5 Wattle and daub

Wattle and daub (Figure 2.5) is an earth construction technique that consists of wooden strips woven together (called *wattle*) which is covered with a mixture of soil and straw (called *daub*). An extremely clayey earth is used which is mixed with a straw or other vegetable fibres to prevent shrinkage cracks upon drying (Houben and Guillaud, 1994). The wattle and daub technique has been traced back many years ago, like adobe, it is still a common building technique used to provide shelter from the external environment in many parts of the world (Wieffering and Fourie, 2009).

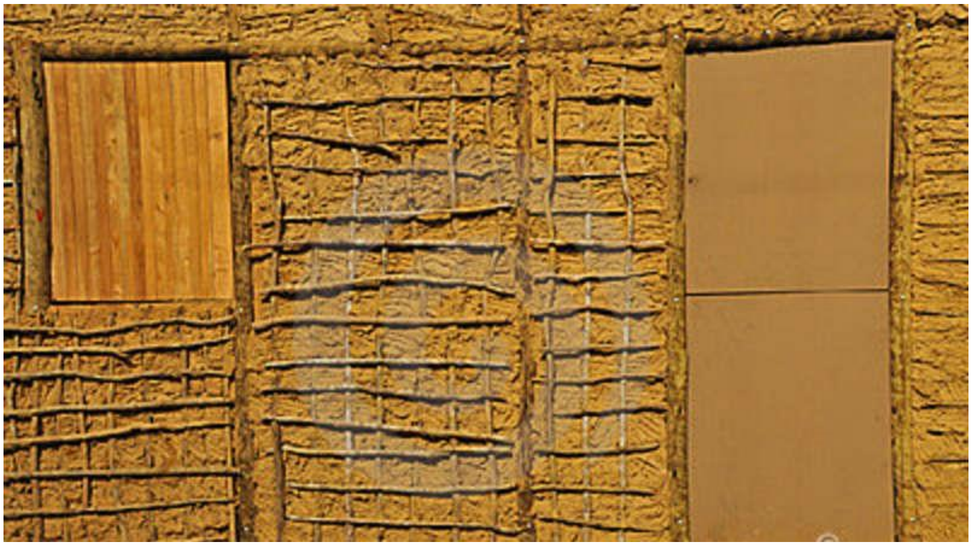


Figure 2.5: Wattle and daub
(Dreamstime.com, 2010)

2.2.2 Stabilisation of soil

Stabilisation or enhancement of soil is the method of adding some materials to the natural soil/earth in order to increase its strength and other properties for the purpose of constructing houses. Stabilising a soil is to improve the properties of the soil in the face of many constraints (Rigassi, 1985). The objectives of stabilisation according to Rigassi (1985) are:

1. To obtain an improved mechanical performance, thus increase the compressive and tensile strengths of the soil;
2. To reduce voids volume created in the soil, thus reduce the shrinkage cracks that would develop when the soil is mixed with water;
3. To improve the durability properties of the soil, thus increase the ability of the soil against rain and any wearing situation.

4.1.1.1 Techniques of stabilisation

There are several ways of stabilising earth. According to Houben and Guillaud (1994), there are four main methods of stabilising earth blocks, they are: stabilisation by reinforcement, stabilisation by water-proofing, stabilisation by cementing and stabilisation by treatment with chemicals. Rigassi (1985) however, identified six categories (Table2.1) of stabilising soil for construction purposes.

Table 2.1: Stabilisation techniques

Technique	Explanation
Increasing density	This is done by creating a dense environment, blocks pores and capillary channels by application of force (compression).
Reinforcing	This technique involves the use of fibrous materials such as fibres form organic origin (agricultural waste), animal origin (wool or hair) and synthetic origin (polythene) in increasing the properties of soil.
Cementation	This technique uses cementious materials to bind and improve the engineering properties of the particles of soil. Some of the materials used are lime, Portland cement, glues and resins.
Bonding	This technique uses chemicals such as acids, flocculants, lime, polymers, etc. to stabilise the soil.
Water-proofing	This technique add materials that expand and seal off access to pores such as bitumen and bentonite to soil to stabilise it.
Water-dispersal	This is done by modifying the water in the soil to improve the properties of the soil. It uses chemicals such as resins, calcium chloride and acids to eliminate the absorption of water.

2.3 LOW-COST HOUSING

This part of the study discusses the constraints of housing availability, the basic principles behind the concept of affordable and low-cost housing and indicators for affordable and low-cost housing concept.

2.3.1 Constraints to housing availability

Lately, much attention has been focused on the access to housing in low income populations. This is noted by undertaking research into construction materials and techniques with the use of local available resources (Yalley, 2012). However, there are some constraints that affect the provision of adequate housing. According to UN Habitat (1991) some of the constraint are as follows:

- Cost and land tenure issues
- Lack of housing finance
- Low income of buyers
- Lack of priority for housing
- Increase urbanisation and population growth
- High cost of imported building materials

Among the constraints, lack of housing finance and high cost of building materials are identified as the most critical constraints (FTI Consulting, 2012), as they are linked to those in the low income bracket typically in rural areas.

2.3.2 The concept of low-cost housing

The use of the terms affordable housing and low-cost housing are used interchangeably. UN Habitat (2011) defined affordable housing as a house that is adequate in quality and location and does not cost such that it prohibits its occupants from meeting other living cost and threatens their enjoyment of basic human rights. Low-cost housing on the other hand is a housing whose total cost for purchase or rent are deemed affordable for those in the median income bracket (Bhatta, 2010). The Australian National Affordable Housing defined low-cost housing as housing which is reasonably adequate in standard and location for low and middle income householders and does not cost much to deprive them of their basic needs (Centrelink, 2008).

The affordability of housing is affected by many factors. The factors are outlined in Figure 2.6 which shows the various components of affordable housing. It principally sets them into two main factors: (1) capital variables which constitute house purchase costs and (2) occupational variables which involve costs associated with keeping the house (UN Habitat, 2011).

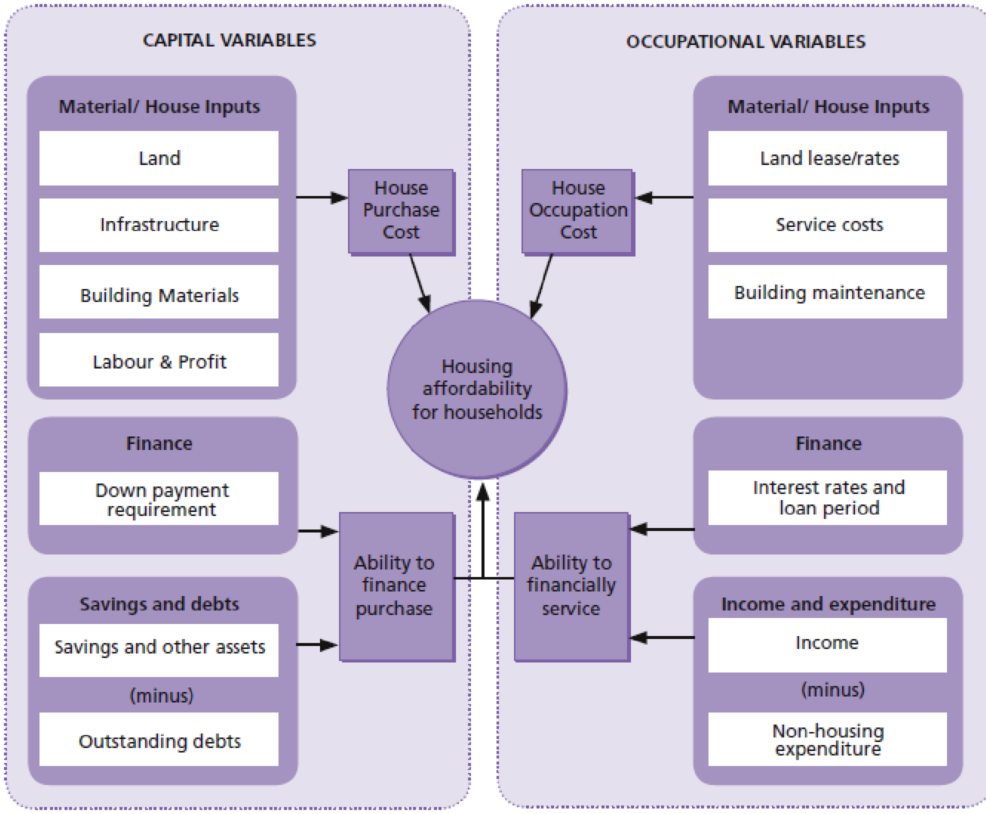


Figure 2.6: Components of housing affordability
(UN Habitat, 2011)

In Africa, the cost of housing is often associated with the cost of the building materials, land prices and the down payment (rent advance) requirement. Since majority of the cost of housing is influenced by the cost of materials (Tataria et al., 2015), developing materials that are inexpensive in formal and informal sectors will eventually lead to providing low-cost housing.

2.3.3 Indicators for low-cost housing

Hulchanski (1995) argues that the choice of housing is a complex decision that depends on economic, social and psychological reasons. Affordability is a key part of this choice. In the United States and Canada, the accepted guideline for house affordability is the cost of housing that does not exceed 30% of the household's income (AFL, 2009, Canada Mortgage and Housing Corporation, 2011). They further explained that if the monthly cost of housing exceeds 30% to 35% of the income of the household, then it is considered unaffordable. The housing affordability is a complex discussion, Canada for example has switched from 20% to 25% rule in the 1950s and in the 1980s it was changed to 30% rule (Hulchanski, 1995). India for example is using 40% rule.

Apart from the percentage income rule, the median multiple indicator is recommended by World Bank for use to measure housing affordability. This is done by dividing the median house price by the gross median household income. There is a scale of 0 to 5 for rating the indicator, 3 to 4 is rated as moderately affordable, 4 to 5 as serious and above 5 is severely unaffordable according to Cox and Pavletich (2012).

Another indicator is the use of hourly wage of a full time worker who is paid the minimum wage set by the government. The affordability is determine by the worker's ability to afford an apartment in the area that they work (Cox and Pavletich, 2012).

These rules and approaches of measuring affordability of housing cannot be adopted in most developing countries because of irregular source of income and high rate of unemployment. Therefore, in addressing the housing problems confronting them, there is the need to consider using locally available and cheap but quality materials for producing low-cost housing to meet their housing needs.

There are no clear cut indicators of the low-cost housing in Africa. However, people measure affordability based on the rent advance they pay and the monthly rent cost. In some parts of Africa such as Ghana, tenants have to pay rent advance sometimes up to five years. This situation requires initial bulk money, and therefore people use the rent advance as indicator of housing cost. Thus, low-cost housing becomes the housing whose rent advance is for few months and monthly rent cost within the means of the tenant.

These interventions are provided to make housing affordable and low-cost to people, but its implementation will be difficult in some parts of the world due to economic situations. It is therefore important to adopt technology and techniques to provide low-cost housing to people in order to shelter their families and properties since it is a basic need for mankind. The use of locally available materials that are abundant and affordable can play an important role in producing low-cost housing.

2.4 ISSUES WITH BUILDING MATERIALS IN AFRICA

Pursuance of sustainable construction is a common goal for both developed and developing countries. It is therefore possible to transfer experiences and technologies, and adapt them to suit local conditions. There is an added impetus towards this goal for Africa where the presence of processed building materials is dependent on the ability to import or produce Portland cement locally at high cost. In the view of Fernandes et al. (2007), the cost of building materials in LEDCs is a single largest contributing factor to housing cost, and they are often transported over long distance at considerable expense. In Africa, conventional building materials are imported or manufactured in urban towns and have to be transported to other parts of a country at long distances which makes the materials very expensive and invariably increase the cost of housing (Yalley, 2012).

Ebohon and Rwelamila (2000) argued that the majority of Sub-Saharan African countries externally procure most of their building materials, with the exception of South Africa. Lately, concerns have been raised over the way residential apartments and commercial buildings are designed and constructed (Chakravarthy et al., 2007). Most of these concerns pertain to energy, environment, sustainable construction methods and technology. The most common raw materials used in construction for example are cement, steel, glass, burnt bricks, and plastics. These materials require high energy to manufacture and need to be transported across vast distances leading to more energy consumption and high cost (Danso, 2013).

Due to these concerns, the adaptation of sustainable materials could be beneficial. The sustainable construction requires a critical review of the existing techniques, practices and materials to improve the situation in Africa where there is lack of housing affordability due to the use of conventional building materials (Kinuthia and Mofor, 2010).

The desire generated by the use of the conventional building materials has resulted in the perception that the locally available materials are not good. Notwithstanding, the focus of researchers is turning towards the use of locally available materials such as agricultural wastes and soil for construction of houses (Kinuthia et al., 2011). For most countries in Africa, the major industrial output is predominantly in the agricultural sector. For these countries, any major breakthrough in the development of locally available material with waste could contribute to sustainable construction (Ezeah et al., 2013).

2.5 SOIL/EARTH AS A BUILDING MATERIAL

2.5.1 Background

Soil or earth is one of the ancient building materials, but is attracting renewed interest. Heathcote (1995) and Ngowi (1997) described earth as the most used construction material in the history of mankind and has been part of the world for thousands of years. Earth masonry construction is widespread in the world in different cultures and countries, both industrialised and developing countries (Achenza and Fenu, 2006). In developing countries earth masonry construction belongs to the local culture and traditional earth building is kept alive in different ways depending on the building traditions (Houben and Guillaud, 1994). However, in industrialised countries, earth construction is becoming unpopular with the exception of some few areas.

Burroughs (2008) argued that although earth has been used in both less economically developed and economically developed countries, the modern construction technologies and material science have resulted in decline of its popularity. Indeed, with the introduction of conventional building materials like cement, lime, steel and others have caused the low interest in the use of soil for building houses in the past century. This has led to not only the increased cost of housing but also environmental impact due to their manufacturing processes and high energy consumption worldwide.

2.5.2 History of soil/earth as a building material

It is not clear as to the date that earth was first used for building houses in human history and how long it has been in used. Berge (2009) argues that the oldest adobe block building was discovered in Tigris River basin as at 7500 BC therefore earth construction has been in existence for many years. On the part of Pollock (1999) the use of earth for construction purposes dates back from Mesopotamia between 5000–4000 BC. There is no agreement on the time or date when mankind began to use earth for construction of houses (Pacheco-Torgal and Jalali, 2012).

Ren and Kagi (1995) stated that earth has extensively been used for housing worldwide, especially in developing countries. Some cities were built with raw earth, such as Babylon in Iraq, Akhetalen in Egypt and Draa valley in Morocco (Easton, 1998). In Ghana, both Elmina and Cape Coast Castles were built with earth bricks in 1482 and 1653, respectively which were used for trans-Atlantic slave trade and are still standing.

In Burkina Faso, the Bobo Dioulasso Grand Mosque and West African Mosque Timbuku were all constructed originally with raw earth (Zami and Lee, 2011). Deboucha and Hashim (2011) also stated that the masonry construction in Malaysia date back 350 years ago as the Stadthurys in Malacca was built in 1650.

2.5.3 Benefits of constructing houses with soil/earth

Constructing houses with soil has many benefits to users of the houses, government and the environment. Previous studies (Zami and Lee, 2007, Morel et al., 2007, Minke, 2009, Maini, 2005, Lal, 1995, Kateregga, 1983, Hadjri et al., 2007, Easton, 1998, Adam and Agib, 2001, Venkatarama Reddy, 2007, Morris and Booysen, 2005, Morton, 2007, Walker et al., 2005) have expressed some of the advantages of constructing houses with soil or earth as follows:

- Readily available in most regions
- Environmentally sustainable
- Promotes cultural heritage and values
- Saves energy
- Reduces construction cost
- Requires simple tools and less skilled labour
- Easy to design and have high aesthetic values
- Provides local job
- Good fire resistance provides indoor thermal comfort
- Promotes self-help construction practices
- Noise control
- Preserves timber and other organic materials
- Earth wall absorbs pollutants

2.5.4 Characteristics of soil for constructing houses

Many tests are available for determining the characteristics of soil, among them are shrinkage, chemical composition, particle size distribution (texture), organic content, Atterberg limits, shear, compaction and mineralogical content. For building purposes, many authors (Stulz and Mukerji, 1981, Spence and Cook, 1983, Gooding, 1993, Doat et al., 1979) have recommended the use of Atterberg limits and particle size distribution tests as the most appropriate parameters.

2.5.4.1 Atterberg limits test

The Atterberg limits test estimates the clay minerals that are present in the soil (Stulz and Mukerji, 1981). It can provide a means for objectively and broadly classifying a soil for a given location (Gray and Frost, 2003). For construction purposes, determining the liquid and plastic limits are sufficient. Therefore the other limits are not important (Stulz and Mukerji, 1981) because the tests are undertaken on small remoulded samples of only the fraction of the required sample that passes through a 425 μm sieve.

Plastic limit (w_{p}) can be defined as the moisture at which a soil will begin to crumble when rolled into thread of about 3 mm in diameter (BS1377:2, 1990)

Liquid limit (w_{L}) is the moisture content at which the soil changes from plastic to liquid states and begins to flow (CE 240, 2010).

Plasticity index (I_p) is the difference between the plastic limit and the liquid limit ($w_{\mathrm{p}} - w_{\mathrm{L}} = I_p$). Table 2.2 presents the meanings of different plasticity index ranges.

Table 2.2: Plastic index and meanings
(British Standard Institute BS 5930, 2015)

Meaning	Range
Non-plastic	0
Slightly plastic	1 – 5
Low plasticity	5 – 10
Medium plastic	10 – 20
High plasticity	20 – 40
Very high plasticity	> 40

2.5.4.2 Particle size distribution test

The particle size distribution (PSD) test determines the amount, usually by mass, of the particles present in a soil sample (Jillavenkatesa et al., 2001). PSD is also known as grain size distribution. The particle sizes are classified as gravel, sand, silt and clay. The summary of soil classification grades of British Standard BS 1377:2 (1990) are presented in Table 2.3.

Table 2.3: Soil particle grading
(BS1377:2, 1990)

Soil classification		Particle size range (mm)
Gravel	Coarse	60 – 20
	Medium	20 – 6.3
	Fine	6.3 – 2
Sand	Coarse	2 – 0.6
	Medium	0.6 – 0.2
	Fine	0.2 – 0.06
Silt	Coarse	0.06 – 0.02
	Medium	0.02 – 0.006
	Fine	0.006 – 0.002
Clay		< 0.002

Table 2.3 indicates that particle size range of 60 mm to 2 mm are gravel, 2 mm to 0.06 mm are sand, 0.06 mm to 0.002 mm are silt and less than 0.002 mm is clay. This is an internationally recognized standard soil particle size range.

2.5.5 Criteria for soil selection

Published studies on the criteria for soil selection for building purposes can generally be characterised in two ways, thus by particle size distribution and by plasticity index (Gooding, 1993).

2.5.5.1 Plasticity index

Three criteria from six (6) studies are presented in Figures 2.7 to 2.9 and are discussed for their suitable application as earth material for building purposes.

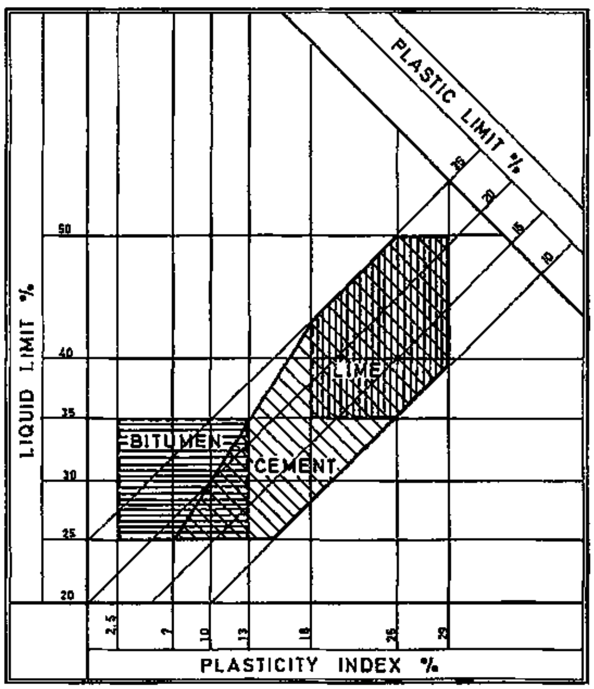


Figure 2.7: Atterberg chart
(Doat et al., 1979)

Figure 2.7 presents a chart of Atterberg limits which was originally developed by Doat et al. (1979) and later used by Stulz and Mukerji (1981) and Norton (1986) for determining the suitability of soil that need binder in order to function satisfactorily as a building material. It shows the various zones within which certain stabilisers (lime, cement and bitumen) should be used as enhancement. This means some types of soil cannot be used for building houses at all, while some will need certain stabilisers to improve their physical and mechanical properties. It should be noted that laterite soils do not necessarily conform to this chart (Stulz and Mukerji, 1981) due to laterite suitability for building purposes without the need for any enhancement. The limits are between plasticity index of 7% to 29% and liquid limit of 25% to 50% for cement stabilised soil, while for lime they are between plasticity index of 18% to 29% and liquid limit of 35% to 50%. For bitumen they are between plasticity index of 2.5% to 13% and liquid limit of 25% to 35%

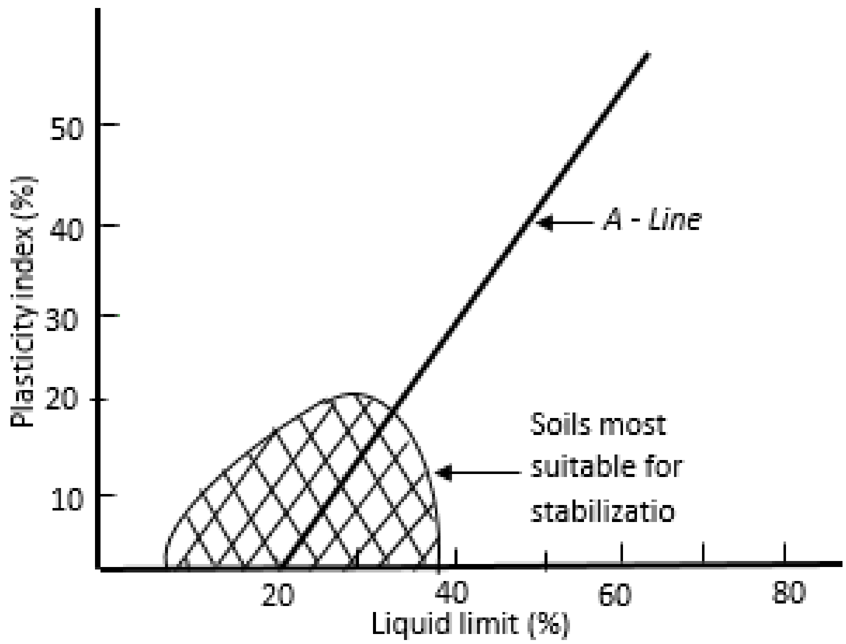


Figure 2.8: Plasticity chart
(Spence and Cook, 1983)

Spence and Cook (1983) also proposed an Atterberg limits zone of soil suitability for stabilisation for soil as shown in the shaded area in Figure 2.8. The limits are between plasticity index 0% to 22% and liquid limit 7% to 39%. These limits are different from Doat et al. (1979) limits. The reason for the difference is that Spence and Cook gave a recommendation of soil for general stabilisation while Doat et al. (1979) recommendation had separate soil suitability for cement, lime and bitumen.

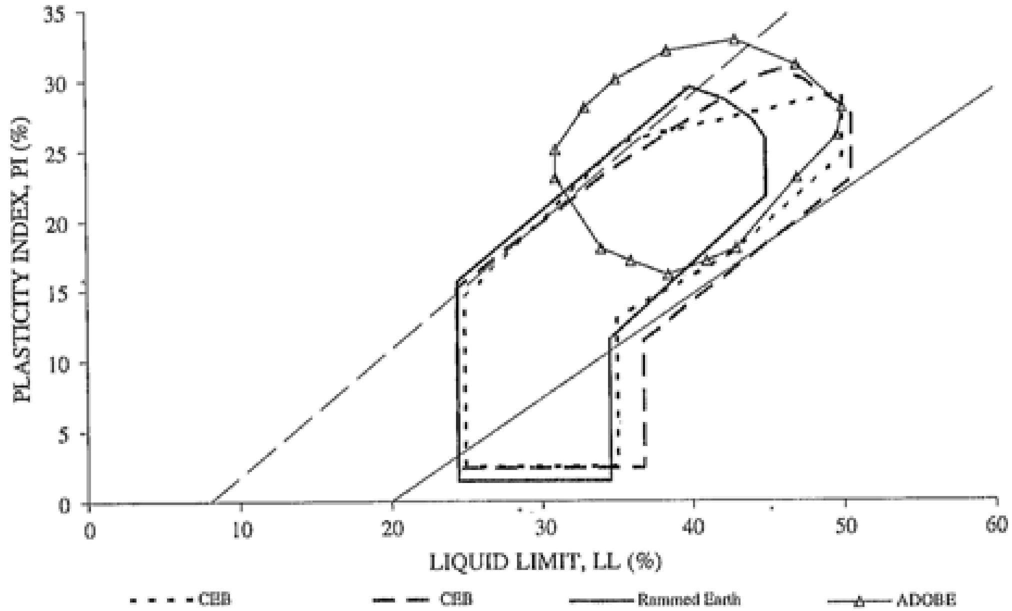


Figure 2.9: Plasticity nomograms
(Delgado and Guerrero, 2007)

The study by Delgado and Guerrero (2007) presented a nomogram plasticity index chart showing the recommended values for three soil block techniques (Figure 2.9). Compressed earth block (CEB) technique was recommended by AFNOR (2001), CRATerre-EAG (1998) and Houben and Guillaud (1994), while RE and adobe techniques were recommended by Houben and Guillaud (1994). However, Delgado and Guerrero (2007) recommended a plasticity index of 16 to 28% and liquid limit of 32 to 46% as a good soil for earth building.

2.5.5.2 Particle size distribution (PSD)

PSD gives information on the soil's ability to pack into a dense structure (Gooding, 1993). There are different recommendations for soil particle sizes that are suitable for different techniques of earth building. Five of these recommendations are put together in a nomogram in Figure 2.10 by Delgado and Guerrero (2007). CEB was recommended by Houben and Guillaud (1994), CRATerre-EAG (1998) and AFNOR (2001). While adobe was recommended by Houben and Guillaud (1994) and CRATerre-EAG (1998), and RE recommended by MOPT. (1992) and Houben and Guillaud (1994).

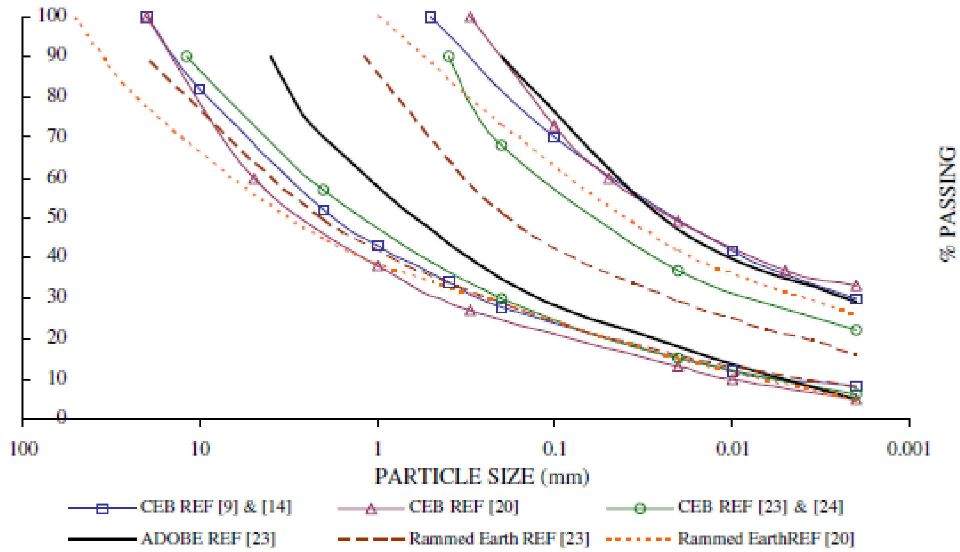


Figure 2.10: Granularity nomograms
(Delgado and Guerrero, 2007)

Another source (Spence and Cook, 1983) made a chart of soil particle size as shown in Figure 2.11. The shaded portion of the chart shows the recommended particle size suitable for soil stabilisation, which are in the range of 0% to 25% for clay, 0% to 25% for silt and 60 to 90% for sand constituents.

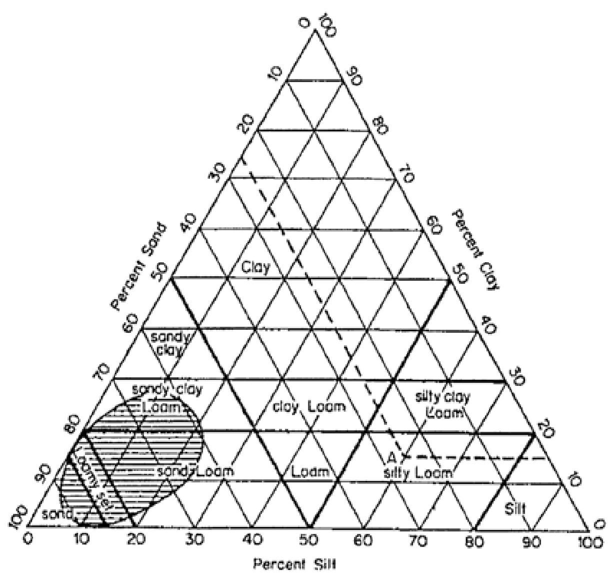


Figure 2.11: Particle size chart
(Spence and Cook, 1983)

In addition, the study by Bengtsson and Whitaker (1986) made recommendations for various techniques of soil particle sizes suitable for construction. The values are presented in Table 2.4.

Table 2.4: Soil grading suitable for construction
(Bengtsson and Whitaker, 1986)

Technique	**Clay (%)**	**Silt (%)**	**Clay & Silt (%)**	**Sand (%)**	**Gravel (%)**	**Sand & Gravel (%)**
Rammed earth	5-20	10-30	15-35	35-80	0-30	50-80
Pressed soil	5-25	15-35	20-40	40-80	0-20	60-80
Adobe	10-30	10-40	20-50	50-80	-	50-80
General purpose	15	20	35	60	5	65

From Table 2.4, it is clear that no single recommendation for soil particle size is accepted worldwide as also confirmed by Ciancio et al. (2013). Since there are different types and characteristics of soil at different places, different recommendations are made to provide suitable grade for building purposes. One important consideration is that, depending on the soil particle size for soil to be used for construction, the recommendations could help to identify the appropriate technique and stabiliser to be used in order achieve optimum result.

Most of these recommendations focused on suitability of soil with binders. The common binders mentioned in the recommendations are cement, lime and bitumen. Not much is seen on soil suitability with other stabilisers such as animal waste and natural fibres. Analysis of soils used in previous studies can be found in Section 3.3.2.

2.5.6 Performance of earth/soil as building material

The performance of earth as a building materials can be determined by three main properties. These are (1) physical properties, (2) mechanical properties and (3) durability properties.

The physical properties are concerned with the physics of the earth/soil, and therefore undergo non-destructive testing. The physical properties are of greater interest for making soil blocks as these will help to determine shrinkage, apparent bulk density size or texture, moisture content, porosity, permeability, adhesion and linear contraction (Yalley, 2012).

The mechanical properties of soil deals with the mechanics of the soil under applied pressure that cause deformation to the soil. The tests applied are destructive to the soil. Bouhicha et al. (2005) expressed mechanical performance of soil blocks with compressive strength, flexural strength and shear strength.

The durability properties of soil deals with the long-term effect of the environment on the soil as a building material. The tests applied are aggressive in nature to predict the future weathering effect on the soil. Bui et al. (2009) characterised the durability with long-term erosion of earthen walls by exposing them in the weather for 20 years. Atzeni et al. (2008) investigated durability by using wear resistance of chemically or thermally stabilised earth-based materials.

More information and analysis of previous studies on the performance of earth/soil as a building material can be found in Section 3.2.

2.5.7 Compaction of earth/soil as a building material

One of the factors that affect the strength of earth blocks is the compaction. Compaction is the process of mechanically densifying a soil by pressing the soil particles together into a close state of contact so that the entrapped air can be expelled from the soil mass (FM 5-410, 1992). Compaction is usually referred to as tamping. Traditional tamping used wooden tamper to manually press the earth in a wooden mould to form the blocks. Currently, earth blocks are compacted with compressed earth block machines such as advance earth construction technologies (AECT) compressed earth block machines (AECT, 2009), CINVA-RAM press (Taylor, 2011), BREPAK block making machine (Webb, 1988), among others. These presses are not expensive as they do not require high energy to operate and their maintenance is not complex (Al-Sakkaf, 2009). CINVA RAM press was the first machine developed to compact soil into a high density block in Colombia during 1952 (Venkatarama Reddy and Gupta, 2005).

The idea of compacting earth is to improve the quality and performance of moulded earth blocks (Guillaud et al., 1995). Soils blocks are often compacted to improve their engineering characteristics, and this can be done in three ways: (1) dynamic compaction, (2) static compaction and (3) vibratory compaction for soil blocks improvement (Venkatarama Reddy and Jagadish, 1993). Compressed soil blocks are generally produced by compaction of soil in a hydraulic or electrical block making machine, in which static and control pressure is applied. Houben and Guillaud (1994) have made a characterisation of moulding pressure for earth/soil blocks as:

- Very low: 1 - 2 MPa
- Low: 2 - 4 MPa
- Average: 4 - 6 MPa
- High: 6 - 10 MPa
- Hyper: 10 - 20 MPa
- Mega: 20 - 40+ MPa

Houben et al. (1996) provided an overview of machines and their compaction pressures as shown in Table 2.5. Table 2.6 provides some of the compaction pressure applied in previous studies.

Table 2.5: Commercial compaction machines and pressure

Machine	Compaction pressure
Altech Geo 50	3.5 MPa
Appro-Techno Terstaram	3.6 MPa + impact
Ausbildungsverbund AVM CINVA Ram	2.0 MPa
Cartem Manual Elephant Block Maker	10.8 MPa
Ceratec Ceraram	2.4 MPa + impact
Concrete Machinery Systems BREPAK	10.8 MPa
Nigerian Building and Road Research NBRRI Block Making Machine	3.0 MPA
Sheltertech Block Press	1 - 2 MPa
Societe Nouvelle Presse a Parpaing	1.1 MPa
TTera Structure TPM	1.2 MPa
Untata 1003	2.5 MPa
Urpata 5005	3.7 MPa

Table 2.6: Compaction pressure used in previous studies

Reference	Compaction pressure
Burroughs (2006)	2.7 MPa
Gooding and Thomas (1997)	2 - 10 MPa
Millogo et al. (2014)	2 MPa
Walker and Stace (1997)	2 MPa
Walker (1995)	2 - 4 MPa
Walker (2004)	2 MPa
Chan (2011)	10 MPa
Cao et al. (2006)	10 MPa

2.6 AGRICULTURAL WASTE FIBRES AS BUILDING MATERIALS

2.6.1 The concept of agricultural waste

Considerable work has been done by research institutions and industries to develop appropriate technologies for the production of building materials from different types of wastes. The need for the adequate management of such wastes and by-products was perhaps desirability in the past, but today it is a compelling necessity.

The concept of agricultural waste as a building material involves the use of agricultural wastes such as the fibres and ashes in addition to other materials to produce building materials that are environmental friendly and affordable in order to produce low-cost and low-energy housing. According to Chan (2011), the agricultural industry generates large quantities of wastes such as pulps, grains and fibres. The improper management of agricultural wastes results in environmental concerns (Turgut and Yesilata, 2008, Demir, 2006). According to Deboucha and Hashim (2011) the incorporation of some of the waste in alternative walling materials will be beneficial to minimise the impact on the environment.

Therefore large amount of agricultural waste if not disposed properly can cause problems that can impact negatively on the health of people. Therefore, the concept of incorporating some of the agricultural waste into building materials is laudable and must be investigated to reap the full benefit.

2.6.2 The concept of agricultural waste fibres as a building material

The use of agricultural waste fibres (natural fibres) as building material is not new in the construction industry, as this concept dates back many centuries ago (Ismail and Yaacob, 2011). According to Li (2002), straw and horsehair were added to mud brick in old Egyptian time, and straw mats were also used as reinforcement in early Japanese and Chinese construction. In the past, some rural areas in Ghana added oil palm fibres to soil for building houses for the purposes of increasing the strength of the soil, prevent wearing of the soil by rain fall and reduce the rate of cracks developing in the walls.

Fibres can be obtained from various agricultural waste such as palm, coconut, bamboo, pineapple leafs, sugar cane and other vegetable. Plant-based natural fibres can be used as reinforcement in composite materials. Studies by Gulbarga and Burli (2013) and Biswas et al. (2009) revealed that the maximum tensile, impact and flexural strengths for natural fibre reinforced plastic (NFRP) composites were 104.0 MN/m^2 (jute-epoxy), 22.0 MN/m^2 (jute-polyester) and 64.0 MN/m^2 (banana-polyester), respectively. This indicates that fibres have some strength properties that can help improve the mechanical properties of some locally available materials to make them strong to be used for building houses which are affordable and environmentally friendly.

2.6.3 Types of agricultural waste fibres

There are many types of agricultural waste fibres that are available and can be obtained through different processes. Below are some of the types of the agricultural waste fibres and their uses.

Coconut husk*:* they can be used to make manufacture boards, insulating boards, roofing sheet and also to reinforce composite materials. Coconut fibre is also known as *coir* and is obtained from the husk of coconut fruit. The fibres are generally available for use in three main ways; (1) bristle (long fibre), (2) mattress (short fibre) and (3) decorticated (mixed fibre) (Ali, 2010). Coconut fruit fibres (Figure 2.12) can be used in the textile industry and is common in Africa and Asia.

Figure 2.12: Coconut husk fibres

Oil palm fibres: they are obtained from different parts of palm tree such as the trunk, leaf, bunch and fruit. Oil palm fibres (Figure 2.13) are obtained from oil palm fruit which originally came from the Western part of Africa in the tropical rain forest where it is processed for its fruits for consumption as edible food and oil, medicine, win, hand craft (Wiafielate and Abiola, 2008) and for industrial use. They are sometimes used as stabiliser in blocks and bricks and also for manufacture boards.

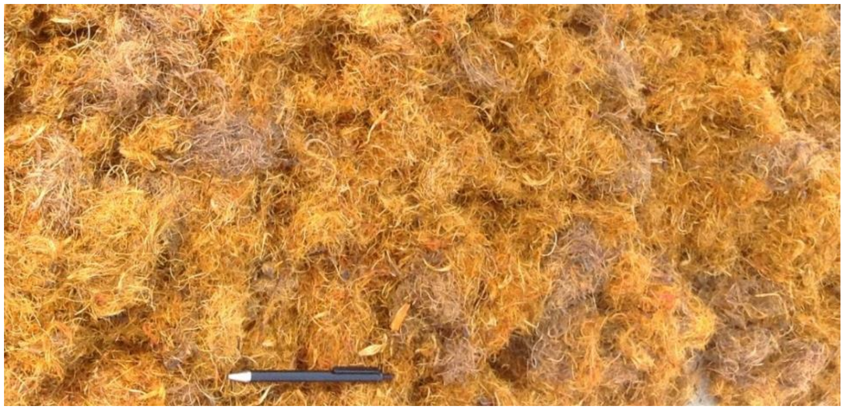


Figure 2.13: Oil palm fibres

Rice husk: is a by-product of rice milling industry and is available in most rice producing areas (Mansaray and Ghaly, 1997). They can be used as a fuel, to make building materials such as manufacture boards and composite material and as pozzolanic ash. Rice husks (Figure 2.14) are an agricultural residue and like oil palm and others, are available in large quantities in some areas. Rice husks and their ash (Shen et al., 2014) have been found to be good for making blocks and cement products.

Figure 2.14: Rice husk
(Markham, 2013)

Groundnut husk: are generally similar to wool in structure (Cook, 2001). Groundnut husk (Figure 2.15) are used in making manufacture boards for construction purposes and also incorporate in soil blocks as reinforcement.

Figure 2.15: Groundnut husk
(Shiridi, 2014)

Banana stalk fibres: are generally obtained from the stem of banana plant and are available in varieties in terms of diameter and lengths. Banana stalk fibres (Figure 2.16) are completely eco-friendly and bio-degradable. They are also manufactured in an eco-friendly manner. Zhu et al. (1994) used banana stalk fibres as reinforcement in cement composite.

Figure 2.16: Banana stalk fibres
(Pacificworlds, 2014)

Wheat straw: are obtained from wheat after the cereals are removed. The alternate way of disposal of surplus wheat straw is of interest and immediate necessity (Talebnia et al., 2010). Wheat straw (Figure 2.17) may be incorporated in a composite material to manufacture roofing units, blocks and wall panels/boards.

Figure 2.17: Wheat straw
(Colourbox, 2012)

Sisal fibres: are fibres obtained from sisal plant with diameter of about 4 μm to 12 μm and lengths of 45 cm to 160 cm (Mascia et al., 2010). The sisal fibres are found commercially in many forms such as cords, strips, fabric and rolls (Freire and Beraldo (2003) and Hashin (1967) cited in Mascia et al. (2010)). In Africa, sisal fibre (Figure 2.18) is used in the craft industry. It can also be used for making composite materials.

Figure 2.18: Sisal fibres
(Miller Waste Mills, 2015)

Jute fibres: are fibres that are extracted from jute plant by either biological or chemical retting processes. It is a long, shiny and soft fibre of about 1 m to 4 m long and about 17 mm to 20 mm diameter (FAO, 2015). Jute fibres (Figure 2.19) are composed primarily of the plant materials cellulose and lignin. They can be used for making sacks, mat, bags, chip boards and composite building materials.

Figure 2.19: Jute fibres
(FAO, 2015)

Cotton stalk fibres: can be obtained from the seed, the stalk and leafs of cotton that are left as by-products. Cotton stalks consist of an outer bark (20% by weight of the stalk) and inner pith, where the outer bark is fibrous and could be utilised as a source of fibres similar to the jute fibres (Reddy and Yang, 2015). Cotton stalk fibres (Figure 2.20) can be used for making fibre boards, panel, door shutters, composite building materials, paper and plaster boards.

Figure 2.20: Cotton stalk fibres
(Ancient Arts, 2014)

Sugarcane fibre: is obtained from sugarcane residue (also called *bagasse*). The stalk of the sugarcane plant have both inner and outer rind and pith, of which the rind is made up of fibrous substances surrounded by a core pith which is usually spongy in nature (Lee and Mariatti, 2008). Sugarcane fibre (Figure 2.21) can be used to reinforced soil blocks and plays important role in enhancing composite materials (Jeefferie, 2011).

Figure 2.21: Sugarcane fibres

Kenaf fibre: is also known as *Hibiscus cannabinus* which is similar to jute and hemp. A mature Kenaf plants can be 5 m tall. Kenaf fibres (Figure 2.22) have been reported to have good flexural strength and are good for many purposes (Aji et al., 2009). Kenaf can be used to produce papers, building materials and animal feeds (Ishak et al., 2010).

Figure 2.22: Kenaf (hibiscus cannabinus) fibres
(Millogo et al., 2015)

Bamboo fibre: is a regenerated cellulosic fibre produced from bamboo (Das, 2015). Bamboo is common in South East Asia and East Asia where they are used as building material. It is also common in Africa for traditional handicrafts and art for weaving basket and for use as building material. Bamboo fibres (Figure 2.23) can also be used as a composite material (Abdul Khalil et al., 2012). The good mechanical properties and the ease of extracting the fibres as well as increased thermal properties make bamboo a useful construction material (Amada et al., 1997).

Figure 2.23: Bamboo fibres
(Budget-t, 2015)

Straw: is one of the ancient materials that was used to reinforced soil block in ancient Egypt and Sub-Sahara Africa. A study by Milutiene et al. (2012) showed that straw is a sustainable building material and can be used also as an insulation material. Straw (Figure 2.24) can also be used as roofing material in traditional mud houses.

Figure 2.24: Straw bale
(Norrgard, 2015)

2.6.4 Properties of natural fibres

Properties of agricultural waste fibres are important to determine the suitability of the fibres for use as building material. According to Ghavami et al. (1999) the properties of natural fibres can be affected by factors such as harvesting time, fibre extraction process, fibre treatment and temperature changes. Table 2.7 provides the properties of fibres used in previous studies.

Table 2.7: Properties of fibres from previous studies

Reference	Fibre	Properties					
		Length (mm)	Diameter (mm)	Water absorption (%)	Specific weight (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Ghavami et al. (1999)	Sisal	382-940	0.06-0.38	140-230	0.8-1.07	580	18
	Coir	67-266	0.13-0.56	60-90	0.77-1.08	150	3
Sen and Reddy (2011)	Sisal	-	-	110	1.37	347-378	15
	Bamboo	-	-	145	1.158	73-505	10-40
	Coir	-	-	93	1.177	95-118	8
	Jute	-	-	13	1.460	400-800	10-30
	Hemp	-	-	8	1.480	550-900	15-45
Millogo et al. (2015)	Kenaf	-	0.13	307	1.04	1000	0.136
Cao et al. (2006)	Bagasse	9.13	0.49	-	-	70.9	-

2.6.5 Effect of moisture on natural fibres

Though natural fibres are good for soil matrix reinforcement, they have some effect when mixed with other materials. One of such problems is high moisture uptake of the fibres (Vasoya, 2007) when come in contact with water. This problem has the tendency of reducing the interfacial bonding of the fibre with the matrix.

Moisture is attracted through the hydrogen bonding of natural fibres due to the hydroxyl and oxygen-containing groups (Jalkanen and Nygren, 2005). Any change in the moisture content of natural fibres many cause changes in the dimension of a composite and also cause swelling and shrinkage when dried (Rowell et al., 2008).

2.6.6 Advantage and disadvantages of natural fibres

The advantages of natural fibres have lately attracted the attention of manufactures (Mahsa, 2006). The advantages have been categorised as follows:

Environmental: the fibres have low energy requirement for production purposes. They also have the properties of neutralising carbon dioxide and also used as compost when disposing off.

Production*:* natural fibres are non-abrasive when handled and also exhibit great formability as compare to conventional building materials.

Component Weight: natural fibres are light weight (less than half the density of glass fibres) and therefore good for producing lightweight materials.

Economic: natural fibres are cheap as compared to other conventional building materials and also cost less in processing.

There are some disadvantages associated with the use of agricultural waste fibres. Swamy (1990) mentioned disadvantages such as shrinkage, decaying due to biological substances, low elasticity and high moisture uptake. Another problems of using natural fibres as a composite material is the dimensional changes when wet and dry, which cause the material to expand and shrink and also causes residual compressive stresses during compaction (Mahsa, 2006).

2.7 SUMMARY

The chapter reviewed the main concepts that underpin the study. These included earth construction, low-cost housing, issues with building materials in Africa, earth/soil as a building material, and agricultural waste fibres as building materials.

The chapter discussed the concept of earth houses. It highlighted the main concepts of earth construction such as the techniques (rammed earth, adobe, compressed earth blocks, cob, and wattle and daub). Furthermore, it explained the stabilisation techniques that exist.

The consideration of low-cost housing discussed the principles that are behind the need, affordability of housing and the ways in which they have been defined. It explained that low-cost housing is a term used to describe dwelling units whose total housing costs for either rented or purchased unit are deemed affordable to those that have a medium of household income.

The issues with building materials in Africa, discussed the existing situation where conventional building materials such as cement, reinforcement bars, among others are imported or manufactured in urban towns and have to be transported to other parts of a country at long distances. This invariably leads to not only high cost of housing but also pollution of the environment and high energy requirement.

Soil or earth is one of the ancient building materials that continue to gain attention in the present built and environment industry worldwide. It was discussed that in developing countries earth masonry construction belongs to the local culture and traditional earth building is kept alive in different ways depending on the building traditions. The introduction of conventional building materials like cement, lime, steel and others have cause the low interest in the use of soil for building houses in the past. Brief history of soil as a building material was highlighted. Benefits of constructing houses with soil/earth were further reviewed.

The concept of agricultural waste as a building material was discussed, which explained that the use of agricultural waste fibres is not new in the construction industry. The utilisation of fibres in materials can be traced back to many centuries ago, and can be obtained from a number of agricultural wastes such as bamboo, coconut, date palm, pineapple leafs, oil palm, sugar palm, sugarcane and vegetable wastes. The properties, effect of moisture as well as advantage and disadvantages of natural fibres were also discussed.

Though this chapter highlights the main concepts of stabilising soil/earth blocks for low cost housing, it is important to search through literature to make a quantitative review of published work. This will help to better understand in broad terms the stabilisation methods, types of test and soil suitability of previous studies in order to establish the gaps that this study seeks to fill. The next chapter (Chapter 3) seeks to address these issues in broader terms.

CHAPTER 3

3 QUANTITATIVE REVIEW OF EMPIRICAL STUDIES

3.1 INTRODUCTION

This chapter reviews the results in the previous studies. It adopts a quantitative approach for which numerical data from previous studies results are extracted and analysed. The main materials used are published works on soil blocks or bricks enhanced or stabilised with fibres and binders. The review consists of two main headings: (1) performance characteristics of enhanced soil blocks, and (2) determination of the suitability of soil for earth construction.

3.2 PERFORMANCE CHARACTERISTICS OF ENHANCED SOIL BLOCKS

3.2.1 Background

A number of studies (Delgado and Guerrero, 2006, Delgado and Guerrero, 2007, Hejazi et al., 2012, Pacheco-Torgal and Jalali, 2012) have reviewed the volume of literature in the enhancement, stabilisation or reinforcement of soil blocks or bricks for construction purposes. Hejazi et al. (2012) reviewed the history, benefits, application; and possible executive problems of using different types of natural and/or synthetic fibres in soil reinforcement. Pacheco-Torgal and Jalali (2012) reviewed some of the environmental benefits associated with earth construction including an overview about its past and present application. It also included a review of economic issues, non-renewable resource consumption, waste generation, energy consumption, carbon dioxide emissions and indoor air quality. In addition, Delgado and Guerrero (2007) offered a useful global view of the different approaches, contributing to the production of a new standard, which was the main purpose of their review. Delgado and Guerrero (2006) also reviewed the state of use of the earth building in Spain. It presented researching organisations, modern projects carried out and the existing manufacturers for compressed earth blocks, and also examine a pair of non-regulatory guides that could act as national reference documents.

There is a significant quantity of literature on the performance of enhanced soil blocks, but at present there is no review of the data from these studies. There remains a need to quantitatively analyse the data in these published works in order to reveal the scale and trend of their results. This is particularly important to this thesis because it aims at investigating the performance properties of enhanced soil blocks. This is relevant because the range of data that will be found in literature can serve as an indication of expected performance ranges to compare with the results that will be obtained in this study. This part of the study, therefore, reviews the existing published works on the effect of stabilisers (fibres and binders) on the technical performance of soil blocks or bricks using the performance measures of density, water absorption, compressive strength, flexural and tensile strength.

3.2.2 Approach

The review adopted a quantitative approach. Numerical data from a number of previous studies' results were extracted and analysed to ascertain the effectiveness of stabilisation methods used. Eighty-one studies were considered and twenty-eight studies used in the quantitative comparison. Two broad categories of enhancement were analysed, fibres and binders. The literature covered a broad range of natural fibres and was primarily obtained from agricultural and industrial residues (see Section 2.6.3). The binders include cement, lime, various polymers and other materials that either react with the soil or set into a crystal lattice after contact with water.

A wide range of tests exist for determining the technical performance of soil blocks. It was apparent that the studies reviewed decided on the types of test to conduct based on the focus of their study and sometimes the availability of test equipment. To compare data from the studies, their results were charted using a common format as a series of scatter diagrams as shown in Figure 3.1. This is a generic illustration to show the approach taken. The abscissa of the chart is the concentration of stabilisation used, consistently expressed as a mass fraction. Where authors expressed concentration in other units, such as volume fraction or as a part of a wider mix description, this was converted. The ordinate is the performance measure of interest expressed in constant units which depended on the performance measure.

For each chart a regression line was drawn which could be one of two types. In cases where a clear maxima is indicated, a second order polynomial curve was fitted the data and the value corresponding to the maximum point on the curve was obtained. In cases where there was a simple trend upwards or downwards a simple linear fit was performed.

The effectiveness of the stabilisation method in the region measured can be expressed in terms of the performance measure per mass of stabilisation added (e.g. MPa per % added). It should be noted that it is very likely that that many stabilisation techniques will have a maximum performance at some concentration, so the effectiveness found can only be considered valid in the region studied.

Soil is a very non-homogenous material and therefore stabilisation is not the only factor that affects block performance. As discussed in Section 3 of this chapter, soil characteristics such as particle size distribution and Atterberg limits, moisture content, drying regime and other factors also have a large impact. As a result of this, a wide variation in unstabilised performance is expected and a subsequent range in stabilised performance. This review attempts to reduce this effect by reporting results in terms of additional performance achieved by the stabiliser rather than fractional improvement.

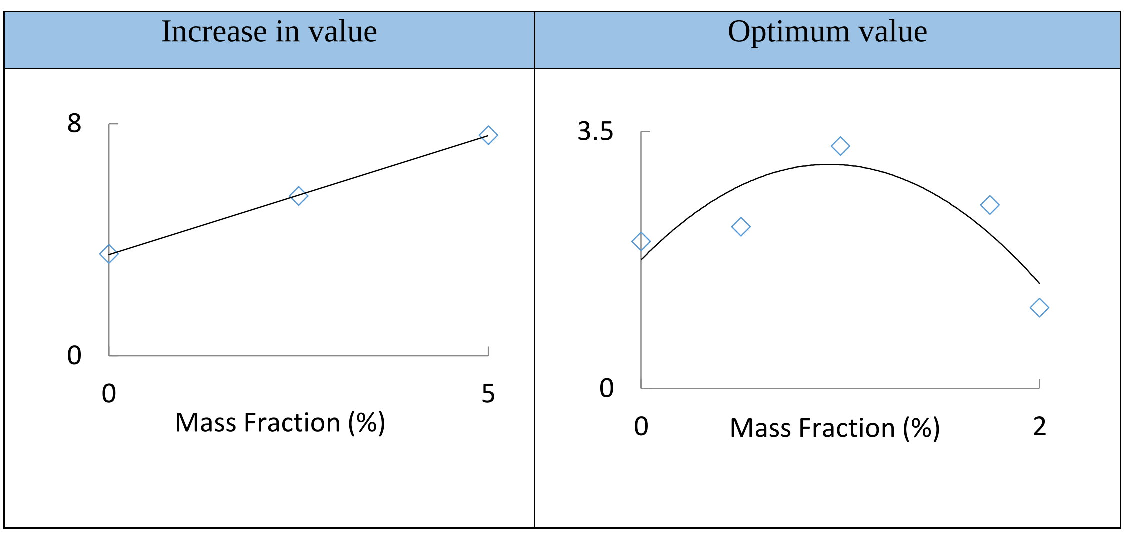


Figure 3.1: Example of charts showing the trend values of the data

3.2.3 Stabilisation methods

This literature review found eighty-one studies which have investigated the use of stabilisation techniques and their effects. Table 3.1 outlines these stabilisation methods. The stabilisation methods identified are with fibres, binders and combination.

Table 3.1: Soil block/brick stabilisation methods of previous studies

Reference	Stabilisation method	
	Fibres	Binders
Quagliarini and Lenci (2010)	Straw	
Yetgin et al. (2008)	Straw	
Piattoni et al. (2011)	Straw	
Parisi et al. (2015)	Straw	
Bouhicha et al. (2005)	Chopped barley straw	
Maher and Ho (1994)	Polystyrene fibre, glass and softwood pulp	
Elenga et al. (2011)	Polyethylene waste nets	
Akbulut et al. (2007)	Scrap tire rubber fibre, polyethylene fibre and Polypropylene fibre	
Yalley and Kwan (2008)	Plastic fibre and palm fibres	
Marandi et al. (2008)	Palm fibres	
Turgut and Yesilata (2008)	Crumb rubber	
Kumar et al. (2006)	Polyester fibre	
Ghavami et al. (1999)	Sisal fibre and coconut fibre	
Gaw and Zamora (2011)	Coconut fibre and coir fibre	
Demir (2006)	Processed waste tea residue	
Kavas (2006)	Boron waste	
Aymerich et al. (2012)	Sheep wool fibre	
Sen and Reddy (2011)	Sisal, Coir, Jute and hemp	
Aguwa (2013)	Coir fibre	
Sreekumar and Nair (2013)	Coir fibre	
Millogo et al. (2015)	Kenaf	
Millogo et al. (2014)	*Hibiscus cannabinus* fibre	
Harper (2011)		Ground granulated blast furnace slag and pulverised fly ash
Degirmenci (2008)		Waste phosphogypsum and natural gypsum
Kouakou and Morel (2009)		Argillaceous minerals
Guettala et al. (2002)		Lime
Millogo et al. (2008)		Lime
Venkatarama Reddy and Lokras (1998)		Lime
Venkatarama Reddy and Hubli (2002)		Lime
Muntohar (2011)		Lime and rice husk ash
Hossain and Mol (2011)		Lime

Reference	Stabilisation method	
	Fibres	Binders
Hossain and Mol (2011)		Lime and fly ash
Heathcote (1995)		Cement
Heathcote (2002)		Cement
Morel and Pkla (2002)		Cement
Thomson (2012)		Cement
Egenti et al. (2014)		Cement
Medjo Eko et al. (2006)		Cement
Montgomery (2002)		Cement
Bahar et al. (2004)		Cement
Walker and Stace (1997)		Cement
Walker (1995)		Cement
Walker (2004)		Cement
Venkatarama Reddy et al. (2007)		Cement
Yalley and Kwan (2008)		Cement
Hossain and Mol (2011)		Cement
Alavéz-Ramírez et al. (2012)		cement, lime and sugar cane bagasse ash
Lima et al. (2012)		sugar cane bagasse ash
Hossain and Mol (2011)		Cement kiln dust and volcanic ash
Ngowi (1997)		Cement, lime, cow-dung and bitumen
Oti et al. (2009)		Cement and lime
Maskell et al. (2015)		Cement, lime and metakaolin
Yu et al. (2015)		Cement, lime, phosphoric acid, hydrofluoric acid and sodium silicate
Nagaraj et al. (2014)		Cement and lime
Shon et al. (2009)		stockpiled circulating fluidized bed combustion ashes
Hossain et al. (2007)		Cement, lime and volcanic ash
Hossain and Mol (2011)		Hydraulic cements, lime and organic polymers
Hossain and Mol (2011)		Cement, lime and asphalt
Hossain and Mol (2011)		Cement and lime
Binici et al. (2005)	Straw, plastic fibres and polystyrene fibre	Cement
Binici et al. (2007)	Straw, plastic fibres and polystyrene fibre	Cement
Segetin et al. (2007)	Flax (harakeke)	Cement
Subramaniaprasad et al. (2012)	Plastic	Cement and lime
Cid-Falceto et al. (2012)	Plastic	Cement and lime
Obonyo et al. (2010a)	Natural fibre	Cement and lime
Obonyo et al. (2010b)	Natural fibre	Cement and lime
Subramaniaprasad et al. (2014)	Plastic	Cement
Arumala and Gondal (2007)	Kenaf fibre	Cement
Juárez et al. (2010)	Lechuguilla natural fibre	Cement
Vilane (2010)	Sawdust	Cement, molasses and cow-dung

Reference	Stabilisation method	
	Fibres	Binders
Chan (2011)	Pineapple leaves fibre and oil palm fruit bunch fibre	Cement
Ismail and Yaacob (2011)	Oil palm empty fruit bunches fibre	Cement
Taallah et al. (2014)	Date palm	Cement
Namango and Madara (2014)	Sisal fibre	Cement
Medjo Eko et al. (2012)	Salvaged steel fibres from used tyres	Cement
Villamizar et al. (2012)	Coconut fibre	Cement and lime
Cai et al. (2006)	Polypropylene	Lime
Villamizar et al. (2012)	Cassava peels	Coal combustion waste
Galán-Marín et al. (2010)	Sheep wool fibre	Alginate
Achenza and Fenu (2006)	Seaweed fibres	Natural polymers
Le and Pickering (2015)	Flax (harakeke)	Polymer

Twenty-two studies stabilised soil blocks or bricks only with fibres and other industrial and agricultural by-products. Thirty-seven studies followed the method that stabilised soil blocks or bricks with only binders. For further enhancement, twenty-two studies combined fibres and binders. Though most of the studies succeed in demonstrating greater improvement, there are still concerns about the manufacturing process of the binder component which can reduce the environmental differential between unfired and fired blocks as well as increasing the cost of producing housing.

3.2.4 Properties and test methods

The focus of previous studies can be categorised in three ways which are physical properties, mechanical properties and durability properties (Table 3.2) . A fourth category which is also important is combinations of these properties. These categorisations were made based on the types of test conducted in the previous studies which are detailed in Table 3.2.

Physical properties are properties other than mechanical properties that depend on the physics of the material, including density, porosity, shrinkage, water absorption, moisture content and thermal expansion. None of the studies focused only on physical properties, though they were often combined with mechanical properties as a comparison. This is because physical property tests are often simple to carry out in the field and may sometimes be used to imply mechanical properties without the need for more complex mechanical testing.

Mechanical properties are those material properties that measure a material's reaction to applied force, such as tensile strength, compressive strength, flexural strength, modulus of elasticity and efflorescence. Eleven studies focused only on mechanical properties. Mechanical properties have been widely studied because it is felt that the perceived limitations of soil blocks are due to problems in mechanical properties.

Durability properties are the properties of a material that resist weathering action, chemical attack, and abrasion. Durability tests attempt to measure the bond holding particles within the wall under the action of simulated erosive forces (Heathcote, 1995). Five studies focused only on durability and in all only eleven studies included durability testing in their work. Those studies also use a wide range of techniques and performance measures that make comparison difficult. This is an indication that durability has seen little research work, however, it is an important test, particularly for high rainfall areas where erosion, blown dust and wear of the soil particles could be critical.

Table 3.2: Types of test conducted by previous studies

Reference	Physical Properties						Mechanical Properties					Durability Properties				
	Density	Porosity	Water Absorption	Moisture content	Dry Shrinkage	Thermal	Compressive	Splitting Tensile	Flexural	Modulus of Elasticity	Efflorescence	First/Post-crack	Freeze Thaw	Wire brush/Abrasion	Drip	Spray
Achenza and Fenu (2006)	✓	✓	✓				✓								✓	
Aguwa (2013)	✓						✓									
Akbulut et al. (2007)							✓									
Alavéz-Ramírez et al. (2012)							✓		✓							
Arumala and Gondal (2007)	✓		✓	✓			✓	✓								
Atzeni et al. (2008)		✓			✓		✓							✓		
Aymerich et al. (2012)												✓				
Bahar et al. (2004)			✓		✓		✓	✓								
Binici et al. (2005)	✓		✓				✓									
Binici et al. (2007)	✓		✓			✓	✓									

Reference	Physical Properties						Mechanical Properties					Durability Properties				
	Density	Porosity	Water Absorption	Moisture content	Dry Shrinkage	Thermal	Compressive	Splitting Tensile	Flexural	Modulus of Elasticity	Efflorescence	First/Post-crack	Freeze Thaw	Wire brush/Abrasion	Drip	Spray
Bouhicha et al. (2005)					✓		✓		✓							
Burroughs (2006)							✓									
Cai et al. (2006)	✓			✓	✓		✓									
Chan (2011)	✓		✓				✓			✓	✓					
Cid-Falceto et al. (2012)															✓	✓
Degirmenci (2008)					✓		✓		✓							
Demir (2006)	✓	✓	✓		✓		✓									✓
Egenti et al. (2014)			✓				✓									
Elenga et al. (2011)	✓			✓	✓		✓		✓	✓						
Galán-Marín et al. (2010)	✓						✓									
Ghavami et al. (1999)			✓				✓	✓								
Gaw and Zamora (2011)					✓		✓									
Gooding and Thomas (1997)	✓						✓									
Guettala et al. (2002)													✓			
Harper (2011)			✓				✓									
Heathcote (1995)															✓	✓
Heathcote (2002)																✓
Hossain et al. (2007)	✓		✓	✓	✓		✓	✓		✓						
Hossain and Mol (2011)	✓		✓		✓		✓	✓		✓						
Ismail and Yaacob (2011)	✓		✓				✓									
Juárez et al. (2010)	✓				✓		✓	✓				✓				
Kavas (2006)			✓		✓		✓									
Kouakou and Morel (2009)		✓			✓		✓									
Kumar et al. (2006)	✓						✓									
Le and Pickering (2015)		✓						✓	✓							
Lima et al. (2012)	✓		✓				✓									
Maher and Ho (1994)							✓	✓	✓							
Marandi et al. (2008)							✓									
Maskell et al. (2015)							✓									
Medjo Eko et al. (2012)	✓						✓	✓	✓							
Medjo Eko et al. (2006)			✓				✓		✓					✓		
Millogo et al. (2008)			✓				✓		✓							
Millogo and Morel (2012)			✓				✓		✓							
Millogo et al. (2014)						✓	✓		✓					✓		✓
Millogo et al. (2015)							✓		✓							
Montgomery (2002)	✓						✓									
Morel et al. (2007)	✓						✓		✓							
Morel and Pkla (2002)							✓		✓							
Muntohar (2011)			✓				✓	✓	✓							
Nagaraj et al. (2014)			✓				✓									
Ngowi (1997)	✓		✓				✓							✓		

Reference	Physical Properties						Mechanical Properties					Durability Properties				
	Density	Porosity	Water Absorption	Moisture content	Dry Shrinkage	Thermal	Compressive	Splitting Tensile	Flexural	Modulus of Elasticity	Efflorescence	First/Post-crack	Freeze Thaw	Wire brush/Abrasion	Drip	Spray
Namango and Madara (2014)							✓		✓							
Obonyo et al. (2010a)																✓
Obonyo et al. (2010b)	✓		✓			✓	✓									
Oti et al. (2009)							✓									
Oti and Kinuthia (2012)							✓									
Parisi et al. (2015)							✓		✓							
Piattoni et al. (2011)							✓			✓						
Segetin et al. (2007)							✓		✓							
Subramaniaprasad et al. (2012)	✓						✓									
Subramaniaprasad et al. (2014)			✓													
Taallah et al. (2014)			✓				✓	✓								
Quagliarini and Lenci (2010)							✓			✓						
Venkatarama Reddy and Lokras (1998)							✓									
Venkatarama Reddy and Hubli (2002)							✓									
Venkatarama Reddy et al. (2007)			✓				✓		✓							
Sen and Reddy (2011)	✓		✓	✓			✓	✓		✓						
Shon et al. (2009)	✓		✓				✓									
Sreekumar and Nair (2013)	✓						✓	✓								
Thomson (2012)	✓						✓								✓	
Vilane (2010)							✓									
Villamizar et al. (2012)			✓				✓		✓							
Walker (1995)	✓				✓		✓	✓								
Walker and Stace (1997)	✓		✓		✓		✓									
Walker (2004)							✓	✓						✓		✓
Yalley and Kwan (2008)						✓	✓									
Yetgin et al. (2008)	✓	✓	✓				✓									
Yu et al. (2015)							✓							✓		
Total	30	6	30	5	15	4	70	15	20	7	1	2	1	6	4	7
	90						113					20				

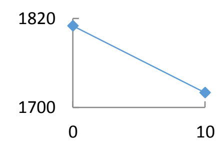
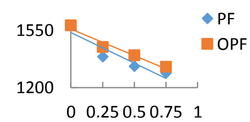
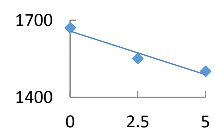
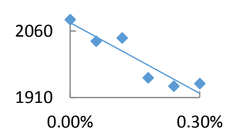
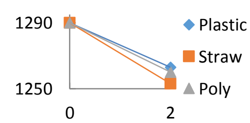
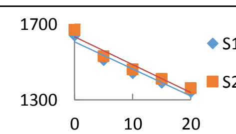
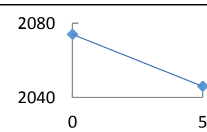
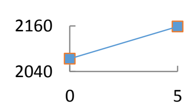
Thirty-four studies combined at least two properties while five studies combined physical, mechanical and durability. This is becoming popular because it offers researchers a variety of tests to investigate the broader properties of enhanced soil blocks.

3.2.5 Density

Eight of the studies that conducted density test of enhanced soil blocks and their results are presented in Table 3.3.

Table 3.3: Density of previous studies

Abscissa is mass fraction (%), ordinate is Density (kg/m^3)

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (kg/m^3/ %)	Unstabilised density (kg/m^3)	Min density (kg/m^3)	Density (kg/m^3)
Achenza & Fenu (2006)	natural polymer		0 - 10	-9.0	1820	1720	
Chan (2011)	Pineapple & oil palm		0.25 – 0.75	-373 – -324	1580	1289	
Demir (2006)	Processed waste tea residue		2.5 – 5.0	-34	1670	1500	
Ismail & Yaacob (2011)	Oil palm	Cement	0.06 – 0.3	-533	2086	1935	
Binici (2007)	Straw, plastic & poly-styrane	Cement	0 - 2	-18.5 – -13.5	1290	1253	
Hossain et al. (2007)		Volcanic ash	5 – 20	-14.8 – -14.4	1670	1340	
Arumala & Gondal (2007)	Kenaf		0 - 5	-5.6	2074	2046	
Arumala & Gondal (2007)		Cement	0 - 5	16.8	2074	2158	

It can be seen from the result (Table 3.3) that all the studies with fibres recorded a negative slope. The density of the unstabilised blocks recorded higher values than the enhanced soil blocks as also confirmed by Ismail and Yaacob (2011) that the average density of fibre bricks was lower than that of the control bricks. This implies that the inclusion of fibres in the soil blocks reduces the density of the blocks, and as the fibre content increase the density of the blocks reduces. This is possible because the fibres reduce the compact and dense nature of the block because the fibres are less dense.

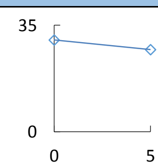
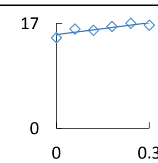
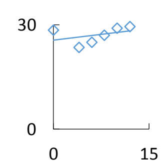
Conversely, the study with binder (cement) recorded an increase in density of the stabilised blocks over the unstabilised. This is explain by Hossain et al. (2007) that the tendency of fine-grained soils is to initially decrease the dry density until the stabiliser (which tends to increase the dry density) acts like a gel and flows into the spaces reducing the air volume. Cement with high specific gravity can produce this effect as confirmed from the increase of dry density of stabilized soil with higher cement content beyond 4% (Anisur Rahman, 1986).

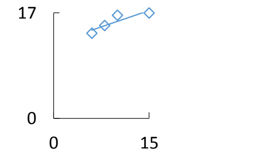
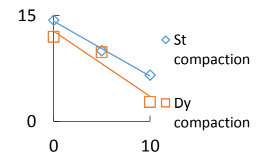
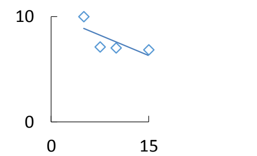
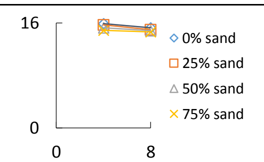
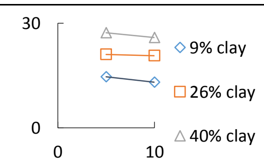
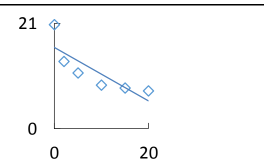
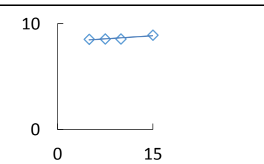
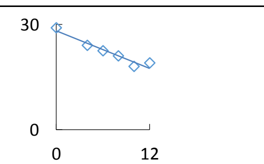
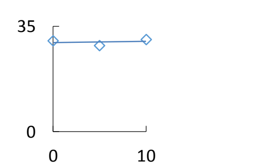
3.2.6 Water absorption

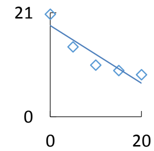
Ten studies conducted a water absorption test, of these, eight were stabilised through a binder and two through fibres. The results of the studies are presented in Table 3.4.

Table 3.4: Water absorption of previous studies

Abscissa is mass fraction (%), ordinate is water absorption (% by mass)

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (%/%)	Unstabilised absorption (%)	Min absorption (%)	Water absorption (%)
Villamizar et al. (2012)	Cassava peel		0 - 5	-0.64	30.2	27	
Ismail & Yaacob (2011)	Oil palm empty fruit bunch		0.06 – 0.3	6.33	14.7*	14.7	
Millogo & Morel (2012)		Cement	2 - 12	0.22	28.5	23.5	

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (%/%)	Unstabilised absorption (%)	Min absorption (%)	Water absorption (%)
Bahar et al. (2004)		Cement	2 - 15	0.35	-	13.68	
Bahar et al. (2004)		Cement	5 - 10	-0.77 - - 0.92	14.29	2.71	
Ngowi (1997)		Cement	5 - 15	-0.26	-	6.85	
Reddy et al. (2007)		Cement	4 – 8	0.05 – 0.18	-	14.66	
Walker & Stace (1997)		Cement	5 – 10	0.08 – 0.30	-	13.1	
Hossain & Mol (2011)		Cement kiln dust	2 - 20	-0. 53	20.7	7.5	
Ngowi (1997)		Lime	5 - 15	0.04	-	8.52	
Millogo et al. (2008)		Lime	2 - 12	-0.89	29	19	
Villamizar et al. (2012)		Coal combustion waste	5 – 10	0.045	30.2	28.7	

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (%/%)	Unstabilised absorption (%)	Min absorption (%)	Water absorption (%)
Hossain & Mol (2011)		Volcanic ash	5 – 20	-0.58	20.7	8.5	

** "Unstabilised" contains none of the stabilisation of interest, but contains other stabilisers which are kept constant throughout.*

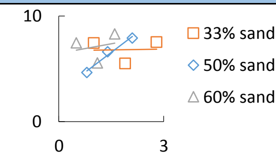
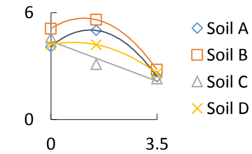
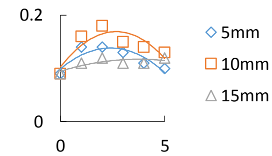
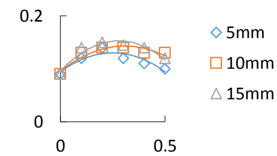
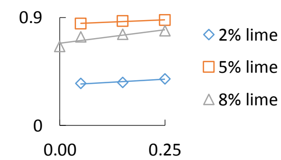
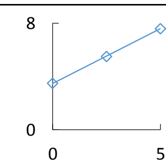
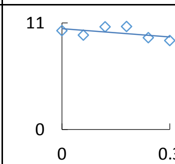
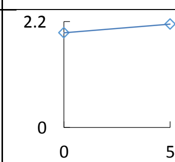
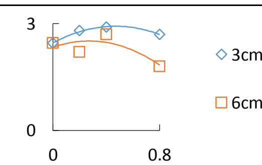
The results for binders indicate variable and fairly neutral water absorption with additional binders. The range recorded was -0.89 % additional absorption for each % of increase in binder (%/%) to 0.35 %/% with a median of 0.02 %/% with half the papers reporting an increase and half a decrease. Explanations about the decrease in absorption are that the binder fills the void between particles reducing porosity, but no explanations about increased absorption were offered in the literature. There were few studies of fibres that included water absorption.

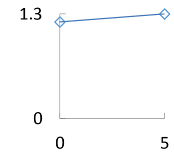
A number of wider studies attempted to soak a block without binders in water and, predictably, found that it quickly disintegrated, so the available studies were restricted to blocks with a combination of binders and fibres. One study (Villamizar et al., 2012) recorded a slight reduction in water absorption with fibres (-0.64 %/%) and the other (Ismail and Yaacob, 2011) a significant increase (6.33 %/%). It is likely that in-general, fibres will increase water absorption as the absorbent nature of fibres creates pathway through soil blocks, thereby allowing more water absorption (Ghavami et al., 1999).

3.2.7 Compressive Strength

Twenty-three of the studies conducted compressive strength tests on stabilised soil blocks/bricks and their results are presented in Table 3.5 (with fibres) and Table 3.6 (with binders). The Turkish standard code for the compressive strength of unfired clay brick is 1 MPa (Turkish Standard 704, 1985, Turkish Standard 704, 1983), while Houben and Guillaud (1994) recommended at least 2 MPa for cement stabilised blocks.

Table 3.5: Compressive strength (with fibres) of previous studies
Abscissa is mass fraction (%), ordinate is compressive strength (MPa)

Reference	Fibre	Range of Mass fractions (%)	Slope (MPa/ %)	Unstabilised Strength (MPa)	Max Strength (MPa)	Compressive strength (MPa)
Piattoni et al. (2011)	Straw	0.025 – 0.075	0.05 – 2.40	-	8.29	
Bouhicha et al. (2005)	Chopped barley straw	1.5 – 3.3	n/a	4.10	5.60	
Akbulut et al. (2007)	Tyre rubber	1 - 5	n/a	0.09	0.18	
Akbulut et al. (2007)	Polyethylene	0.1 – 0.5	n/a	0.09	0.14	
Cai et al. (2006)	Polypropylene	0.05 – 0.25	0.15 – 0.45	0.66*	0.88	
Demir (2006)	Processed waste tea residue	2.5 – 5.0	0.82	3.50	7.60	
Ismail & Yaacob (2011)	Oil palm empty fruit bunch	0.06 – 0.3	-2.86	10.22*	10.65	
Villamizar et al. (2012)	Cassava peels	0 - 5	0.036	1.97	2.15	
Millogo et al. (2014)	Hibiscus cannabinus	0.2 - 0.8	n/a	2.45	2.90	

Reference	Fibre	Range of Mass fractions (%)	Slope (MPa/ %)	Unstabilised Strength (MPa)	Max Strength (MPa)	Compressive strength (MPa)
Arumala & Gondal (2007)	Kenaf	0 - 5	0.02	1.20	1.30	

** "Unstabilised" strength is with a binder, but no fibre. Binder content is kept constant*

Table 3.5 shows nine studies that conducted compressive strength tests with various fibres as the enhancement agent. The results show the three types of trend (1) a slope with a positive gradient indicating an increase in compressive strength with additional fibres, (2) a slope with a negative gradient indicating a falling strength with additional fibres and (3) a rise to a maxima followed by a fall. The gradients, cover a wide range with a minimum of -2.86 MPa per % added, a maximum of 2.4 MPa per % added and a median of 0.8 MPa per % added. Five of the studies (Arumala and Gondal, 2007, Cai et al., 2006, Demir, 2006, Piattoni et al., 2011, Villamizar et al., 2012) obtained a positive gradient, while Ismail and Yaacob (2011) obtained a negative gradient. The balance of the papers (Akbulut et al., 2007, Bouhicha et al., 2005, Millogo et al., 2014) show a definite optimum fibre content. This content varies between 0.1% and 5% with a median of 1.0%.

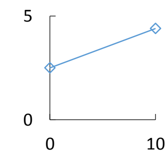
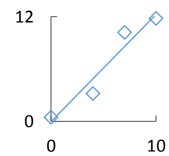
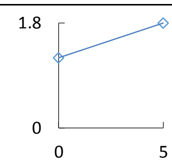
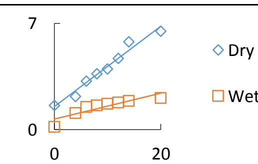
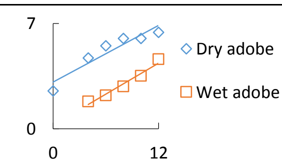
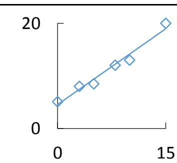
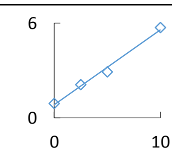
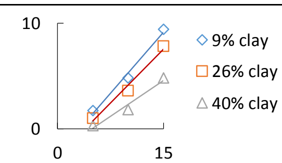
Of the studies that did not include a binder as well as fibres, the lowest optimum found was 0.14 MPa which is well under the recommendations, and the highest from soil stabilised by only fibre was 8.29 MPa. Soils alone varied from 0.09 MPa to 5.15 MPa and the improvement due to fibres alone ranged from 0.04 MPa to 1.17 MPa with a median of 0.43 MPa. Interestingly, the improvement followed the soil strength very well with the exception of Ismail and Yaacob (2011). Pearson's coefficient is r = 0.8 without Ismail & Yaacob but only r = 0.09 with it. This demonstrates the importance of the soil matrix for the effectiveness of fibre reinforcement. As the soil matrix is so important, the fractional improvement obtained with fibres was found to be in a quite narrow range (4% to 117% with a median of 26%).

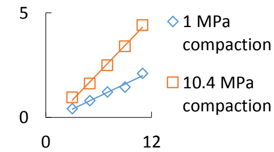
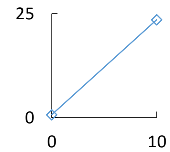
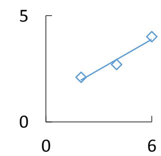
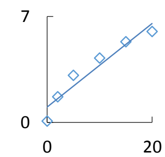
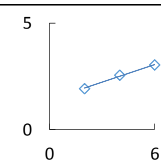
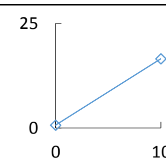
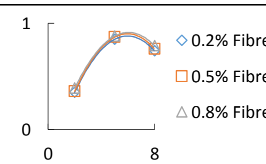
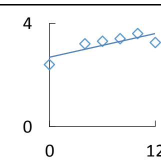
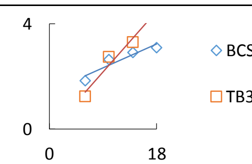
There was a wide range (0.025 – 5%) of fibre content used in these studies. This make the quantity of fibre content a very important contributing factor to strength development of the reinforced soil blocks. Another important factor to strength development is fibre aspect ratio (the ratio of length to diameter of the fibre). However, most of the literature did not consider the fibre aspect ratio in their studies.

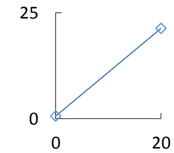
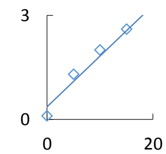
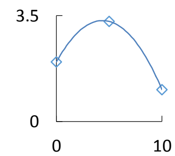
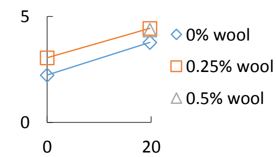
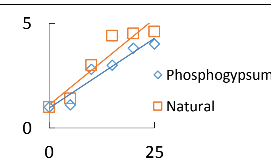
Table 3.6 presents the result of compressive strength tests of soil blocks enhanced with different types of binder from 17 published studies.

Table 3.6: Compressive strength (with binder) of previous studies

Abscissa is mass fraction (%), ordinate is compressive strength (MPa)

Reference	Binder	% Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Compressive strength (MPa)
Achenza & Fenu (2006)	natural polymer	0 - 10	0.19	2.50*	4.40	
Medjo Eko et al. (2012)	Cement	4 – 10	1.23	0.50*	11.60	
Arumala & Gondal (2007)	Cement	0 - 5	0.12	1.20	1.80	
Bahar et al. (2004)	Cement	4 - 20	0.086 – 0.27	1.60	6.50	
Millogo & Morel (2012)	Cement	4 – 12	0.31 – 0.35	2.50	6.40	
Guettella 1997, cited by Morel et al. (2007)	Cement	2.5 - 15	0.96	5.10	20.00	
Walker, 2000, cited by Morel et al. (2007)	Cement	2.5 - 10	0.48	0.90	5.70	
Walker & Stace (1997)	Cement	5 - 15	0.45 – 0.77	-	9.40	

Reference	Binder	% Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Compressive strength (MPa)
Gooding & Thomas (1997)	Cement	3 - 11	0.20 – 0.43	-	4.40	
Alavez-Ramirez et al. (2012)	Cement	0 – 10	2.29	0.64	23.5	
Burroughs (2006)	Cement	2 – 6	0.48	-	4.01	
Hossain & Mol (2011)	Cement kiln dust	2 – 20	0.28	0.10	6.01	
Burroughs (2006)	Lime	2 – 6	0.28	-	3.03	
Alavez-Ramirez et al. (2012)	Lime	0 – 10	1.59	0.64	16.50	
Cai et al. (2006)	Lime	2 – 8	n/a	-	0.88	
Millogo et al. (2008)	Lime	2 - 12	0.076	2.4	3.6	
Venkatarama Reddy & Hubli (2002)	Lime	6 - 18	0.10 – 0.26	-	3.30	

Reference	Binder	% Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Compressive strength (MPa)
Alavez-Ramirez et al. (2012)	Lime + bagasse ash	0 – 20	1.03	0.64	21.30	
Hossain & Mol (2011)	Volcanic ash	5 – 20	0.15	0.10	3.10	
Villamizar et al. (2012)	Coal combustion waste	5 – 10	n/a	1.97	3.31	
Galán-Marín et al. (2010)	Alginate	0 - 19.75	0.070-0.078	2.23	4.44	
Degimenci (2008)	Gypsum	5 -25	0.13 – 0.16	1.00	4.60	

* *"Unstabilised" strength is with fibres, but no binder. Fibre content is kept constant.*

The results indicate that the vast majority of the studies s that an increase in binder results in an increase in compressive strength. This increase ranged from 0.07 MPa per % added to 2.29 MPa per % added with a median of 0.28 MPa per % added. In terms of compressive strength improvement, Portland cement is the most successful binder but also the most variable (range = 0.09 – 2.29 MPa/%, median = 0.54 MPa/%). Portland cement has the advantage of reacting with water forming various strong and rigid hydrates which fill spaces and bind particles together independent of reactions with the soil (Bahar et al., 2004, Millogo and Morel, 2012). Though pozzolanic reactions with clays in the soil will occur, they play a small part in strength formation (Millogo and Morel, 2012) and are smaller than the disadvantages associated with clay in the soil (Walker and Stace, 1997). This is followed by materials relying on pozzolanic reactions such as volcanic ash (0.15 MPa/%) and cement kiln dust (0.28 MPa/%) and lime. The material will finally set around the particles rather than react with them such as gypsum (0.16 MPa/%) and then polymers (Alginate – 0.08 MPa/%).

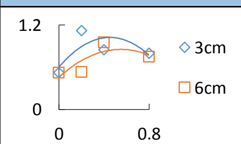
As many binder reactions do not appear to level off in the regions studied, maximum strength is likely to be an economic or environmental rather than technical constraint, however as an indication of scale within the region of the studies analysed which range from 1% to 20%, the maximum compressive strength recorded was 21 MPa of which 20 MPa was improvement from the cement binder at a 10% mass fraction. An exception to this trend was lime which relies on pozzolanic reactions with clays (Millogo et al, 2008). Once clays are all reacted, the lime simply forms a filler material which is porous and weak (Muntohar, 2011, Venkatarama Reddy and Hubli, 2002). The optimum concentration of lime, therefore is dependent on the clay content of the soil but varies between 1.5% and 14% in the studies including lime as a binder.

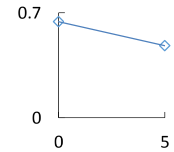
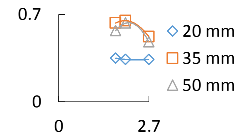
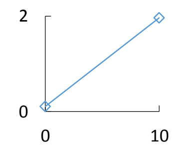
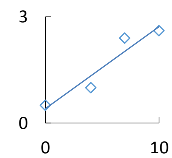
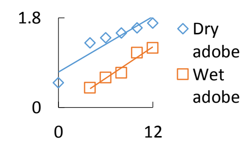
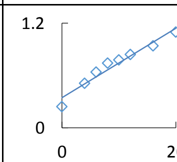
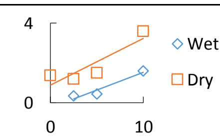
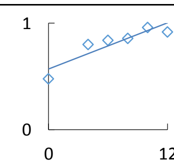
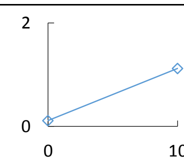
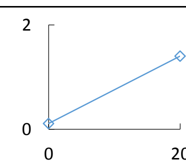
The performance of the binders was relatively insensitive to initial strength of the soil and the range of fractional improvement was from 50% to 5900%, though there is no reason to assume that this couldn't be improved upon if it were desirable to do so. As the use of binders enhances the strength of the soil matrix by increased cohesion between particles, their use also should also aid the pull-out performance of fibres and therefore the performance of fibre stabilised blocks. Four studies combined fibres and binders, however the results were, in fact quite similar to those for soil without binders. The median improvement for fibres in a binder-stabilised soil was 0.22 MPa, whereas the medium improvement for natural soils was 0.33 MPa. It is likely that other factors such as compression and clay content have contributed as much to fibre effectiveness as binder content.

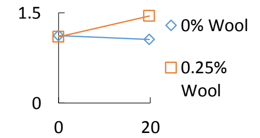
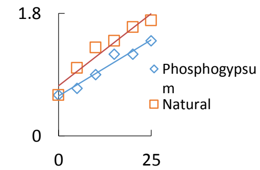
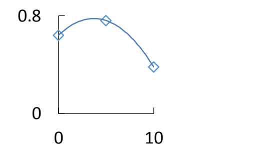
3.2.8 Flexural and tensile strength

Ten studies conducted flexural strength test of enhanced soil blocks. The results are presented in Table 3.7.

Table 3.7: Flexural and tensile strength of previous studies
Abscissa is mass fraction (%), ordinate is Flexural or tensile strength (MPa)

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Flexural strength (MPa)
Millogo et al. (2014)	*Hibiscus cannabinus*		0.80	n/a	0.52	1.12	

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Flexural strength (MPa)
Villamizar et al. (2012)	Cassava peel		5.00	-0.032	0.64*	0.64	
Medjo Eko et al. (2012)[†]	Salvaged steel fibres		1.70 – 2.70	n/a	-	0.63	
Alavez-Ramirez et al. (2012)		cement	0.00 - 10.00	0.19	0.11	1.96	
Medjo Eko et al. (2012)		cement	4.00 – 10.00	0.23	0.50*	2.60	
Millogo & Morel (2012)		Cement	2.00 - 12.00	0.093 – 0.11	0.50	1.70	
Bahar et al. (2004)[†]		Cement	4.00 - 20.00	0.039	0.24	1.10	
Walker (2004)[†]		Cement	2.50 - 10.00	0.17 – 0.23	1.37	3.58	
Millogo et al. (2008)		Lime	2 - 12	0.04	0.48	0.92	
Alavez-Ramirez et al. (2012)		Lime	0 - 10	0.10	0.11	1.12	
Alavez-Ramirez et al. (2012)		Lime + bagash	0 - 20	0.06	0.11	1.40	

Reference	Fibre	Binder	% Fibre /Binder (Range)	Slope (MPa/%)	Unstabilised Strength (MPa)	Max strength (MPa)	Flexural strength (MPa)
Galán-Marín et al. (2010)		Alginate	0.0 - 19.75	-0.003 – 0.018	1.05*	1.45	
Degimenci (2008)		Gypsum	5 - 25	0.033 – 0.042	0.60	1.70	
Villamizar et al. (2012)		Coal combus tion waste	5 – 10	n/a	0.64	0.76	

** “Unstabilised” contains none of the stabilisation of interest, but contains other stabilisers which are kept constant throughout. † Tensile strength.*

The result show a very similar trend of results to compressive strength, with binders showing a generally rising flexural strength with increased concentration and fibres showing a maximum value. There were very few studies with fibres and so the maxima recorded must be considered as tentative. Millogo et al. (2014) report a maximum of 1.12 MPa, an improvement of 0.6 MPa which compares to an improvement of 0.45 MPa for compressive strength from the same study, so the ratio of flexural to compressive strength improvement ($\sigma_{f,max}/\sigma_{c,max}$) is 133%.

Conversely, Villamizar et al. (2012) reported a reduction in flexural strength, however these results are based on only two points, one with fibres and one without and so is unlikely to represent an optimum fibre content. The median overall strength achieved was 0.6 MPa, 22% of the median compressive strength achieved with fibres. A notable feature of fibres in both tension and compression is that the failure is more gradual, acting more like a ductile than a brittle material (Cai et al., 2006). This is ascribed to the fibres changing large cracks to many micro-cracks which hold the soil particles together (Medjo Eko et al., 2012) and form a bridge after the soil has cracked (Aymerich et al., 2012). It has also been proposed that fibres act to reduce the propagation of cracks in the soil matrix (Millogo et al., 2014).

More studies were available involving a range of binders. The maximum recorded flexural strength improvement was 2.2 MPa 11% of the maximum compressive strength improvement, however as with compressive strength, this is likely to be a socioeconomic choice. More relevant for a binder is the rate of improvement. The maximum change is 0.24 MPa/% which is 10% of the maximum rate of improvement for compressive strength. The median change of strength imparted by a binder is 0.1 MPa/% and the median ratio of flexural to compressive strength change was 25%. The hierarchy of binders was also similar to that found for compressive strength with cement displaying the highest and most variable improvement (range = 0.003 – 0.24 MPa/%, median = 0.10 MPa/%). Next, pozzolanic additives and lime (range = 0.04 – 0.1 MPa/%, median = 0.06 MPa/%) and then other non-reactive materials such as Gypsum (0.042 MPa/%) and Alginate (0.018 MPa/%). One study of a pozzolanic material (Villamizar et al., 2012) showed a clear optimal concentration and another with lime (Millogo and Morel, 2012) showed a weak optimum.

3.2.9 Erosion

Search through literature revealed that there are few studies conducted on durability properties of soil blocks. The test that was found among the few studies on durability is erosion. Two main erosion tests are available: (1) water spray test, and (2) drip test. Heathcote (2002) described eight kinds of water spray test and three kinds of drip test developed. These deferent approaches make it difficult to chart graphs with the data from the few studies available due to different ways the results were presented. Table 3.8 presents three common results of studies conducted using drip test on enhanced soil blocks.

Table 3.8: Drip test results of previous studies

Source	Fibre/Binder	Depth of pitting (mm)	Erodability index (E_I)	Rating
Achenza and Fenu (2006)	Seaweed	2.0	2	Slightly erosive
	Polymer and seaweed	0.0	1	None-erosive
Thomson (2012)	Cement	0.5	2	Slightly erosive
Cid-Falceto et al. (2012)	Cement	6.0	3	None-erosive

E_I 1=0 (None-erosive), E_I 2=0<5 (Slightly erosive), E_I 3=>5≤10 (Erosive), E_I 4=>10 (Very erosive)

The result indicates that both studies (Achenza and Fenu, 2006, Thomson, 2012) obtained pitting depth between 0 and 2mm which passed the erosion test. The result means that the enhanced soil blocks were within the rating of none-erosive and slightly erosive, implying that the enhanced soil blocks are less erosive. Another study on drip test by Cid-Falceto et al. (2012) on drip test also found that the cement stabilised blocks pitting depth was practically zero, while non-stabilised blocks depth of pitting was 6 mm (erosive). This is possible because the fibres and the binders hold the particles of the soil together, and so doing prevent the soil particles from washing away by water.

The water spray test conducted by Cid-Falceto et al. (2012) showed that the stabilised blocks passed the erodability test while the unstabilised blocks failed. The problem is that Cid-Falceto et al. (2012) used the erodability index to characterised the performance of the blocks instead of percentage reduction 60 mm/h requirement of the test. An interesting point from a previous study (Walker, 2004) on erosion is that block geometry has influence on the performance. Walker (2004) found that "erosion of blocks increased, at constant density, broadly in proportion to each block's surface area: volume ratio. For example, erosion of the 225 × 110 × 81 mm blocks (surface area: Volume = 0.052 mm^{-1}) was, on average, 2.3 times greater than identical blocks measuring 295 × 140 × 96 mm (surface area: Volume = 0.042 mm^{-1})".

As can be seen above, there are different tests and approaches of determining the erosion performance of soil blocks from the previous studies. Testing for durability performance of soil blocks is important due to the fact that the blocks easily erode under rain fall (water). However, few studies have been conducted to measure the durability properties of stabilised soil block.

3.2.10 Summary

Based on the review of the performance characteristics of enhanced soil blocks or bricks, the following remarks can be made:

1. Studies that enhanced the soil blocks or bricks with fibres mostly recorded an increase in compressive strength until an optimum was reached at a median strength of 0.43 MPa above the unstabilised soil strength, and then further fibres reduced the strength of the block. This optimum varied, but was in the very low percentages with a median value of 1%. The effectiveness of fibres was also very dependent on the soil matrix and can be considered to be capable of improving the strength of a block by up to 117%, but more likely to be in the region of 20 – 50%. The addition of binders

generally continually increased the strength of the block with a median improvement of 0.28 MPa per % added with the exception of lime which relies on reactions with clay and therefore has an optimal concentration which depends on the clay content. It is likely that other materials relying on pozzelanic reactions would have a similar peak, however this was not shown in the studies found.

2. Flexural strength displays very similar behaviour to compressive strength, but based on only a couple of studies, fibres appear to have a proportionally better performance. Fibres also make the blocks fail more gradually which may be important for earthquake prone areas. As with compressive strength, the addition of binders generally improves flexural strength, however materials which rely on pozzolanic reactions don't display as pronounced a defined maxima as with compressive strength.

3. The inclusion of stabilisers has a very variable effect on water absorption with as many studies reporting an increased absorption as a decreased absorption. This is contrary to generally the accepted theory which states that binders should reduce water ingress and fibres should increase it.

4. In general, the inclusion of fibres in the soil blocks reduced the density of the blocks, and as the fibre content increased the density of the blocks reduced. Conversely, the use of binders increased the density of the stabilised blocks over the unstabilised.

5. Few studies focused on improving the durability property of enhanced soil blocks which is one of the major problems with earthen construction, while the majority of the previous studies tested for physical and mechanical properties.

The review concludes that, in general, fibre and binder inclusion in soil blocks enhances the performance characteristics of the blocks. This part of the chapter reviewed the existing published works on the effect of stabilisation on the performance characteristics of soil blocks. Binders are, in general more effective on a mass-fraction basis, however, the supply of fibres is usually at a lower cost and a reduced environmental impact, and therefore may have a better performance on a pro rata cost basis. The performance data presented in this review should help determine if this is the case where cost and impact data can be locally determined.

The major drawback of earth as construction material is the durability especially when in contact with water. However, few studies have been conducted on durability properties whereas most of the studies are geared towards physico-mechanical properties. Therefore more research is required into improving the durability properties of enhanced soil blocks. This implies that researchers and practitioners need to know the right content of fibre to be used for stabilising soil blocks and also check the amount of binders to be used in order not to erase the sustainable aspect of earthen construction. This study will therefore perform physical, mechanical and durability property tests on the blocks it aims to produce.

3.3 DETERMINATION OF THE SUITABILITY OF SOIL FOR EARTH CONSTRUCTION

3.3.1 Background

Different kinds of soil exist worldwide with different characteristics which are likely to have effects on the performance of the structures that are constructed with the soil. It is imperative to identify the characteristics of any obtainable soil before using it for construction purposes. Natural soil exists in distinct composition of sizes, for which certain proportions of these sizes can make a good material for building structures. This presents the need for testing any given soil before it is used in the construction industry as a filling or structural material. The issue is that given the fact that not all soils are suitable and some classes are better depending on the technique, it is necessary to use some way for evaluating them (Delgado and Guerrero, 2007).

3.3.2 Survey of available published literature on particle size and Atterberg limits

This section of the review has been put together to highlight the properties of soil types used in previous studies for their experimental activities. The discussions have been categories into two: (1) particles size distribution, and (2) Atterberg limits. Explanation of particle size distribution and Atterberg limits of soil have been provided in Section 2.5.5.

3.3.2.1 Particle size distribution

The results of particle size distribution of soil from 32 different studied by 21 authors from published literature are presented in Table 3.9 showing the clay, silt sand and gravel contents. The table also shows the recommendations of appropriate technique(s) made for each type of soil based on the soil suitability criteria discussed above (see Section 2.5.5.2).

From the soil suitability criteria discussion, the types of soil used in the previous studies could be recommended for rammed earth (RE), compressed earth blocks (CEB) and adobe blocks (ADO) techniques for earth construction. These recommendations are based on the extreme ends of all the five particles size distribution recommendations for soil suitability criteria discussed in Section 2.5.5.2. While outside recommendation (OR) falls outside the criteria for soil suitability for earth construction. It must be noted that the soils work for the tested technique even though recommendations on soil properties suggest they are not ideally suited. This however, means that the criteria for soil selection may well be imperfect, due to the fact that the soils work for other techniques outside the recommended techniques.

The entire tests performed were on CEB and ADO blocks. It can however be seen that the techniques which most of these blocks/bricks were tested are outside the recommended. From the results, only one soil type from study by Alavéz-Ramírez et al. (2012) was within the recommended soil technique for only rammed earth. For compressed earth blocks technique only, two types of soils from studies (Akbulut et al., 2007, Yetgin et al., 2008) could be recommended. While soil samples from eight studies (Yetgin et al., 2008, Quagliarini and Lenci, 2010, Piattoni et al., 2011, Ngowi, 1997, Muntohar, 2011, Ismail and Yaacob, 2011, Degirmenci, 2008, Bouhicha et al., 2005) could be within the recommended technique for adobe blocks.

Some of the soil particle sizes from the previous studies could be recommended for use in two techniques of earth construction. Soil from previous studies (Bouhicha et al., 2005, Binici et al., 2005, Bahar et al., 2004) could be within the recommended techniques of rammed earth and compressed earth blocks. This means that such soil particle sizes could be used for making both compressed earth blocks and rammed earth construction.

Table 3.9: Soil particle size distribution of previous studies

Source	**Particle Sizes by Mass (%)**					**Technique Tested***	**Recommended Technique***
	Clay (≤0.002 mm)	**Silt (0.002 -0.06 mm)**	**Fine Sand (0.06 - 0.2 mm)**	**Coarse Sand (0.20 - 2 mm)**	**Gravel (2 - 60 mm)**		
Achenza and Fenu (2006)	0.50	51.50	40.7	7.30	-	ADO	OR
Akbulut et al. (2007) Soil A	25.00	73.00	2.00		-	CEB	OR
Soil B	20.00	65.00	15.00		-	CEB	CEB
Soil C	16.00	59.00	25.00		-	CEB	CEB/ADO
Alavéz-Ramírez et al. (2012)	4.30	23.10	72.60		-	CEB	RE
Arumala and Gondal (2007)	10.00	87.00	3.00			CEB	OR
Bahar et al. (2004)	62.00		30.30		7.70	ADO	RE/
Binici et al. (2005)	32.04	24.52	43.44		-	ADO	RE/CEB
Bouhicha et al. (2005) A	40.00	45.00	8	7.00	-	ADO	OR
Soil B	28.00	29.00	23	20.00	-	ADO	ADO
Soil C	21.00	39.00	5	35.00	-	ADO	RE/CEB
Soil D	26.00	42.00	4	27.00	-	ADO	RE/CEB
Cai et al. (2006)	25.00	61.8.00	13.20		-	CEB	CEB/ADO
Degirmenci (2008)	81.00		18.00		1.00	ADO	ADO
Elenga et al. (2011) B	48.00	16.00	36.00		-	CEB	OR
Y	46.00	24.00	30.00		-	CEB	OR
Galán-Marín et al. (2010)	32.00	45.00	22.50		-	ADO	RE/CEB/ADO
Hossain and Mol (2011)	16.00	35.00	42.00		7.00	CEB	RE/ADO
Hossain et al. (2007) Soil 1	16.00	35.00	42.00		7.00	CEB	RE/ADO
Soil 2	30.00	48.00	22.00		-	CEB	CEB/ADO
Ismail and Yaacob (2011)	16.00	37.00	47.00		-	CEB	ADO
Kouakou and Morel (2009)	25.50	30.00	44.50		-	ADO	CEB
Li et al. (2014)	31.30	67.00	1.70		-	ADO	OR
Marandi et al. (2008)	3.40	13.00	83.00		-	ADO	OR
Maskell et al. (2015)	16.00	46.00	33.00		-	ADO	RE/ADO
Medjo Eko et al. (2006)	40.00	24.00	35.00		1.00	CEB	OR
Muntohar (2011)	20.00	33.00	47.00		-	CEB	ADO
Ngowi (1997) Soil M	48.00	25.00	27.00		-	CEB	OR
Soil T	14.50	22.50	63.00		-	CEB	ADO
Piattoni et al. (2011)	22.40	49.90	24.50		3.20	ADO	ADO
Quagliarini and Lenci (2010)	28.50	48.50	12.70		10.30	ADO	ADO
Vilane (2010)	10.00	5.00	85.00		-	ADO	RE/ADO
Villamizar et al. (2012)	13.63		84.80		1.57	CEB	RE/ADO
Yetgin et al. (2008) A1	14.00	20.00	66.00		-	ADO	RE/ADO
A2	19.00	28.00	53.00		-	ADO	CEB/ADO
A3	26.00	23.00	51.00		-	ADO	ADO
A4	12.00	16.00	72.00		-	ADO	RE/CEB/ADO
A5	33.00	20.00	47.00		-	ADO	CEB

*** RE= rammed earth; CEB= compressed earth block; ADO= adobe; OR= outside recommendation***

Again, soil samples used in previous published works (Hossain et al., 2007, Cai et al., 2006, Akbulut et al., 2007, Yetgin et al., 2008) may be recommended for making compressed earth block as well as adobe blocks (see Table 3.9). Soil characteristics from the studies by authors (Yetgin et al., 2008, Villamizar et al., 2012, Vilane, 2010, Hossain and Mol, 2011, Hossain et al., 2007) may also be recommended for two techniques, thus rammed earth construction and adobe blocks.

In addition, the results of soil particle sizes of soil types from previous studies (Yetgin et al., 2008, Galán-Marín et al., 2010) may be suitable for application in three techniques of earth construction, which are rammed earth construction, compressed earth blocks and adobe blocks. This implies that some soil types are such that they could be applicable in three different techniques for earth construction. It could therefore be said that any type of soil that is found to be suitable for construction purposes can be applied for between one and three techniques of earth construction, with majority within one and two and just few for three techniques.

However, the results show that some of the soil particle sizes were found to be outside the criteria of suitability of soil for earth construction. Five soil types from studies (Ngowi, 1997, Arumala and Gondal, 2007, Akbulut et al., 2007, Achenza and Fenu, 2006, Bouhicha et al., 2005) fall within this bracket. Though these soils are found to be outside the recommended, they can be mixed with other soil to improve their compliance.

3.3.2.2 Atterberg limits

Table 3.10 presents the results of Atterberg limits of 25 soil samples of 18 authors from published literature. The results show the liquid limits, plastic limits and plasticity index of the previous studies. In addition, recommendations of appropriate technique(s) for each soil sample are made based on the plasticity index criteria discussed above. The recommended techniques are based on the extreme ends of all the six Atterberg limits recommendations for soil suitability criteria discussed in Section 2.5.5.1. This again brings into question the reliability of the criteria for soil suitability selection.

Table 3.10: Atterberg limits of previous studies

Source		Atterberg Limits		Technique Tested*	Recommended Technique*
		Liquid limit (%)	Plastic Limit (%)	Plastic Index		
Achenza and Fenu (2006)		24.00	21.00	3.00	ADO	RE
Aguwa (2013)		50.00	18.33	31.67	ADO	OR
Akbulut et al. (2007)	Soil A	65.00	35.00	30.00	CEB	OR
	Soil B	62.00	35.00	27.00	CEB	OR
	Soil C	65.00	42.00	23.00	CEB	OR
Alavéz-Ramírez et al. (2012)		25.28	13.28	12.00	CEB	RE/CEB
Aymerich et al. (2012)		28.00	17.00	11.00	ADO	RE/CEB
Bahar et al. (2004)		39.00	24.00	15.00	ADO	CEB
Bouhicha et al. (2005)	Soil A	56.76	23.43	33.00	ADO	OR
	Soil B	32.72	14.94	18.00	ADO	RE/CEB
	Soil C	31.63	17.82	14.00	ADO	RE/CEB
	Soil D	39.67	21.85	18.00	ADO	RE/CEB/ADO
Cai et al. (2006)		34.50	16.90	17.60	CEB	RE/CEB
Chan (2011)		45.85	22.38	23.47	CEB	CEB/ADO
Degirmenci (2008)		56.41	35.71	20.70	ADO	OR
Egenti et al. (2014)	Soil A	33.00	18.00	15.00	CEB	RE/CEB
	Soil U	35.00	21.00	14.00	CEB	RE/CEB
Elenga et al. (2011)	Soil B	48.40	23.20	25.20	CEB	RE/CEB
	Soil Y	62.93	24.74	38.16	CEB	OR
Galán-Marín et al. (2010)		34.80	19.10	15.70	ADO	RE/CEB
Hossain et al. (2007)	Soil 1	39.00	20.00	19.00	CEB	RE/CEB/ADO
	Soil 2	52.00	23.00	29.00	CEB	OR
Hossain and Mol (2011)		39.00	20.00	19.00	CEB	RE/CEB/ADO
Ismail and Yaacob (2011)		63.00	32.00	31.00	CEB	OR
Jafari and Esna-ashari (2012)		41.30	25.20	16.10	ADO	RE/CEB
Kouakou and Morel (2009)		38.00	20.00	18.00	ADO	RE/CEB/ADO
Li et al. (2014)		36.40	18.60	17.80	ADO	RE/CEB/ADO
Maskell et al. (2015)		24.00	16.00	8.00	ADO	RE/CEB
Medjo Eko et al. (2012)		45.11	31.56	13.55	CEB	ADO
Millogo et al. (2014)		38.00	20.00	18.00	CEB	RE/CEB/ADO
Morel and Pkla (2002)	TS	30.00	21.00	9.00	CEB	RE/CEB
	TM	60.00	29.00	31.00	CEB	OR
Muntohar (2011)		41.00	25.00	16.00	CEB	CEB
Ngowi (1997)	Soil M	31.00	19.00	12.00	CEB	RE/CEB
	Soil T	50.00	24.00	26.00	CEB	CEB
Piattoni et al. (2011)		26.40	18.40	8.00	ADO	RE/CEB
Villamizar et al. (2012)		35.00	17.00	18.00	CEB	RE/CEB/ADO

* *RE= rammed earth; CEB= compressed earth block; ADO= adobe; OR= outside recommended*

From the results, soil sample used in previous studies (Ngowi, 1997, Muntohar, 2011, Bahar et al., 2004) could be recommended for compressed earth blocks technique. Soil Atterberg limits from study of Achenza and Fenu (2006) could be recommended for rammed earth construction, while the soil type in the study by Eko et al. (2012) could be recommended for adobe blocks. These results indicate the suitability of soil types for only one technique of earth construction.

Soil types in previous published works (Yalley and Kwan, 2008, Ngowi, 1997, Galán-Marín et al., 2010, Cai et al., 2006, Bouhicha et al., 2005, Alavéz-Ramírez et al., 2012, Piattoni et al., 2011) are within the recommended techniques for rammed earth construction and compressed earth blocks. While soil type in the study by Chan (2011) could be recommended for compressed earth blocks and adobe blocks. This implies that some of the soil's Atterberg limits of the published works can be applicable in two techniques of earth construction.

Some of the soil types from the studies (Villamizar et al., 2012, Hossain and Mol, 2011, Hossain et al., 2007, Bouhicha et al., 2005) could be recommended to be suitable for use in rammed earth construction, compressed earth blocks and adobe blocks techniques. These results confirm that some soil samples can be suitable for use in three earth construction techniques.

Contrary, some of the soil types from earlier published studies (Ismail and Yaacob, 2011, Hossain et al., 2007, Degirmenci, 2008, Bouhicha et al., 2005, Akbulut et al., 2007) were found to be outside recommended for construction purposes. As was the situation in the soil particle size, these soils can be improved with the addition of other soil to meet the recommended criteria.

A suitable raw soil for earth construction should contain sufficient amount of particle sizes to prevent damage of materials such as excessive shrinkage and bond failure. The clay content in soil is of major importance in earth construction, since it binds the larger particles together. However, soils with more than 30% clay have very high shrinkage and swelling effect, together with their tendency to absorb moisture, which may result in development of cracks in the end product. Conversely, a very low content of clay in soil will also result in poor bonding of the other particles, which may cause bound failure in the end product. Therefore, soil with very low or very high content of clay and sometimes silt may need the inclusion of stabilisers in order to be suitable for construction purposes.

3.3.3 Summary

Testing any given soil before it is used in the construction industry as a structural material is crucial. This part of the study reviewed the previous published studies' criteria for selecting suitable soil for construction purposes. Based on the soil properties found the literature, recommendations were made for the suitability of different soil samples for three main techniques (Adobe blocks, rammed earth and compressed earth blocks) application in earth construction. Some of the soil samples were found to be appropriate for more than one technique application. The study found 6 published studies on the criteria for soil suitability of making blocks. The criteria were in two main approaches: particle size distribution analysis; and Atterberg limits. In addition, 57 test results of published literature on particle size and Atterberg limits of soil samples for blocks and bricks were found. Due to some instances where the same soil sample were found to be suitable for one criterion and outside recommended for the other, the study recommend the adoption of both criteria (PSD and Atterberg limits) for determining the suitability of soil for construction purposes. In view of this, both PSD and Atterberg limits will be adopted to test the suitability of the soil samples that will be used in conducting the experimental work in this research. More information about the tests and properties of the soil samples used in this study can be found in Chapters 4 and 5.

3.4 GAPS IDENTIFIED IN LITERATURE

The need to undertake this research is the gaps identified during the review of the relevant literature on stabilisation or enhancement of soil/earth blocks/bricks. The majority of these studies were conducted in developed countries (Montgomery, 2002 from United Kingdom; Obony, 2011 from United States of America, Akbulut, 2007 from Turkey, Heathcote, 2002 from Australia, Achenza and Fenu, 2006 from Italy, Burroughs, 2006 from Australia, Delgado & Guerrero, 2006 from Spain, Chan, 2011 from Malaysia, Gidigasu, 1976 from Netherland, Graham & Burt, 2001 from Mexico, Adam and Agib, 2001 from France). Developing countries are the most likely to benefit from this technique due to high housing deficit. However, not much research work is seen in these areas. There is the need to fill this gap by extending the study on the phenomenon to the developing economies like Ghana for more conceptual and empirical evidence to better assess the strength and durability properties of soil blocks made in Ghana and to advance the production of low-cost houses in developing countries.

Secondly, most of the studies in the phenomenon used cement, lime and other binders as the stabiliser for the blocks (Walker and Stace, 1997, Walker, 1995, Heathcote, 2002, Bahar et al., 2004, Millogo and Morel, 2012, Reddy et al., 2007, Gooding and Thomas, 1997, Hossain & Mol, 2011, Ngowi, 1997, Atzeni et al., 2008, Burroughs, 2006, Oti and Kinuthia, 2012). Other studies also combined cement with fibres (Binici et al., 2005, Arumala and Gondal, 2007, Juárez, Guevara, Valdez and Durán-Herrera, 2010, Vilane, 2010, Medjo Eko et al., 2012, Obonyo et al., 2012, Chan, 2011). For sustainability purpose, natural fibres for enhancing soil blocks without binders has most benefits.

Thirdly, the previous studies on stabilisation of soil blocks with agricultural waste fibres used materials like oil palm empty fruit bunch fibres (Ismail and Yaacob, 2011), pineapple leaves and oil palm fruit bunch (Chan, 2011), plastic fibres (Yalley and Kwan 2008), straw (Quagliarini and Lenci, 2010; Yetgin et al., 2008; Piattoni et al., 2011; Bouhicha et al., 2005), *Hibiscus cannabinus* fibre (Millogo et al., 2014), kenaf fibre (Arumala and Gondal, 2007), cassava peels (Villamizar et al., 2012) and seaweed fibres (Achenza and Fenu, 2006) as enhancement for soil blocks/bricks. Indeed, the results of these studies indicated an improvement of the physical and mechanical properties of the blocks/bricks. There is a need to extend the study to other agricultural waste such as oil palm fruit, coconut and sugarcane (bagasse) fibres as an enhancement of the mechanical as well as durability properties of soil blocks to be used as walling materials for producing low cost houses. This will provide empirical evidence and literature relating to the production of low-cost houses in Ghanaian perspective. It will again, provide options to the government of Ghana and other developing countries where earth is abundant for providing affordable houses for their citizen in order to reduce the housing deficit.

Fourthly, few studies included durability test in their research work. Durability is one of the problems associated with earthen construction, which requires research works to address or reduce the effect in order to ensure confidence of users in the material as good building material. This is an important test, particularly for high rainfall areas such as Ghana where erosion, blown dust and wear of the soil particles could be critical. The current study will incorporate durability test in the research to extend the empirical data on erosion and wearing characteristics of soil blocks reinforced with natural fibres, and boost the confidence of practitioners and users of improve durability of the material.

Few studies (Millogo and Morel, 2012; Millogo et al., 2014; Gooding and Thomas, 1997) applied constant pressure during the manufacturing of the blocks, indeed studies have shown that the higher the pressure the denser and stronger the blocks. However, the rate (speed) of application of the pressure in compacting the blocks during manufacture has not been studied, whether they affect the strength properties of the blocks or not. This study attempts to establish whether the rate of application of pressure in producing blocks affect the strength of the blocks.

In addition, most studies that enhanced soil block with fibres used arbitrary lengths of the fibres without considering the length-to-diameter ratio. There is the need to determine the appropriate aspect ratio of fibres that will provide peak strength of the blocks.

Finally, there is lack of information on the internal mechanisms of fibre-soil composite and failure modes of the composite. This is important to earth construction practitioners to provide additional insight on the characteristics of fibre enhanced soil block as a composite building and construction material.

PART III

EXPERIMENTAL METHODS, RESULTS AND DISCUSSION

CHAPTER 4

4 PROPERTIES OF EXPERIMENTAL SOILS

4.1 INTRODUCTION

The aim of this chapter is to determine the properties of the soil samples that were used for making the soil blocks. The chapter consists mainly of the types of soil samples, preparation of the soil samples, methods for determining the soil properties, results and analysis.

4.2 TYPES OF SOIL SAMPLES

Three main soil samples were obtained for the study. They are: (1) soil sample obtained from Horsea Island, Portsmouth England, United Kingdom; (2) Red soil which was obtained from Kumasi, Ghana; and (3) Brown soil obtained from Sunyani, Ghana.

The Horsea Island (HI) soil sample was selected due to the proximity of the location to the research institution (University of Portsmouth) and is also within the recommended limits of soil generally specified for earth construction. This sample was used for pre-test experiment which was conducted to establish the relevance of the application of different compaction speed on soil blocks, in order to determine the effect of applying low and high speed of compaction in manufacturing soil blocks. It was also used to study the internal mechanism of the fibre-soil matrix.

The Red (R) and Brown (B) soil samples were used for the main fieldwork after the pre-test laboratory work. These soil samples were selected for the study because they are the two main kinds of soil that are used for earth construction in Ghana. They also represent a range of properties with one of the soils (B) within the limits generally specified for earth construction, while the other (R) is partially outside the limits. Any earth structure found in the country is made with either R or B soil. They were therefore appropriate to be used since Ghana is the main research area where the field work was conducted.

4.3 PREPARATION OF SOIL SAMPLES

The soil samples were obtained from the various locations and prepared (Figure 4.1) for the block making. The sites were located and cleared of all bushes, shrubs, hedges and trees. Top soils were removed to depth of about 300 mm because they contain organic matter and have low bearing capacity which makes it unsuitable for construction purposes.

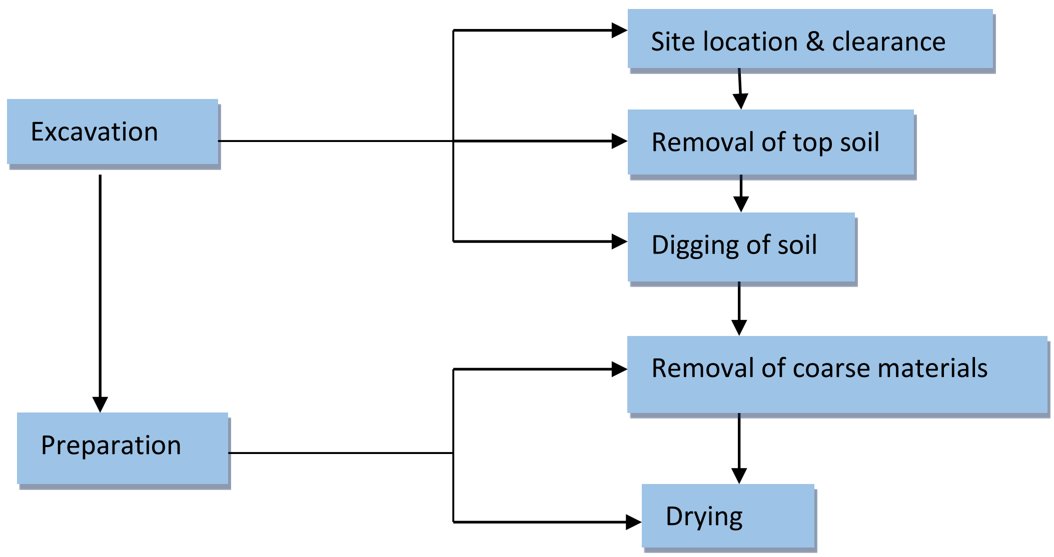


Figure 4.1: Process involved in obtaining and preparing soil samples

The soil samples were dug using simple hand tools such as machete, pick axe, spade and shovel. These tools were used because of the representative quantity of the soil required for making the blocks. After the soil samples were obtained, they were sieved through a 10 mm sieve for bigger particles and unwanted materials such as tree root, stones, etc to be removed and allowed to dry under a shed by air for two weeks. To ensure uniform drying, the soil samples were turned over once a day.

4.4 METHODS FOR DETERMINING SOIL PROPERTIES

This section consists mainly of a compaction test to determine optimum moisture content (OMC) and maximum dry density (MDD), particle size distribution, dry moisture content, Atterberg limits and chemical composition/elements of the soil samples.

4.4.1 Determination of particle size distribution

This test was used to determine the proportion of particles of different sizes within the soil samples. It is important to determine the particle size distribution (PSD) of the soil samples because it can affect the strength and durability properties of the enhanced soil blocks, as smaller particles are likely to pack between the fibres and the matrix to improve the strength. This test was conducted in accordance with British Standards Institute BS 1377:2 (1990). Wet sieve analysis test was used to determine the mass proportion of various particle size of the soil from gravel to coarse sand while sedimentation test was also used to determine the mass proportion of the soil from coarse silt to fine clay.

The soil sample was quartered to sizeable proportion. The sample was weighed and soaked in water in a bucket. The mixture was stirred frequently for at least 1 hr. It was then washed a little at a time through 5 mm to 63 µm test sieve. Figure 4.3 illustrate the hydrometer test process. The results obtained from the sieve analysis and the hydrometer tests were put together and the PSD graph plotted.

Figure 4.2: Hydrometer test process

4.4.2 Compaction test

The objective of this test was to obtain the relationship between compacted dry density and soil moisture content. This is important to determine the percentage water content required to prepare the soil blocks with maximum dry density. This test covered the determination of dry density of soil samples when compacted over a range of moisture contents.

The main apparatus for the compaction test consisted of a cylindrical mould and metal rammer (2.5 kg) (Figure 4.2). The compaction test procedure was carried out in accordance with Biritish Standards Institute BS 1377:4 (1990). The mould was weighed with base plate attached (m_1). The extension of the mould was attached and placed on the base of the compaction testing machine. A quantity of moist soil was placed in the mould such that when compacted it occupied about one-third of the height of the mould body. 27 blows from the metal rammer were dropped from a controlled height of 300 mm above the soil.

The above process was repeated for the second and third layers, so that the amount of soil used was sufficient to fill the mould with the surface not more than 6 mm above the upper edge of the mould. The extension of the mould was removed with the excess soil stroke off and the surface levelled to the top of the mould using a straight edge (Figure 4.2). Any coarse particles that were removed during the process of levelling was replaced by finer material from the soil sample and well pressed in. The soil and the mould with base plate was then weighed (m_2).

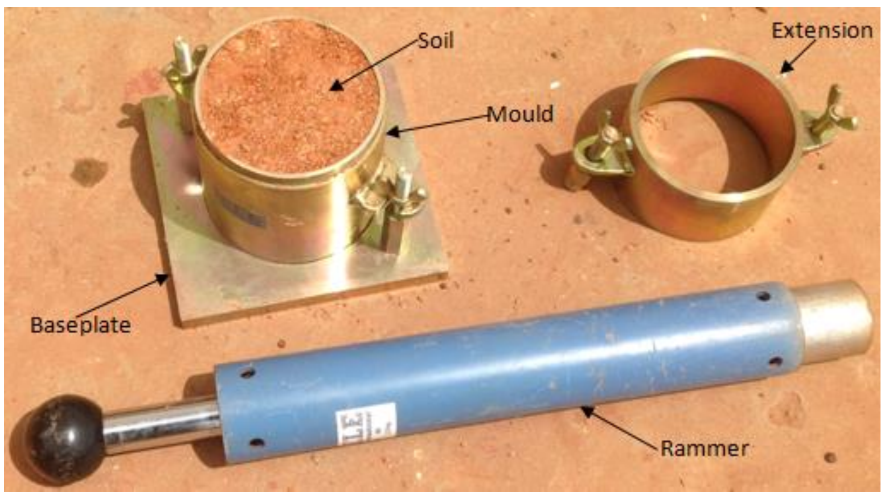


Figure 4.3: Apparatus for compaction test

The bulk density of each compacted specimen was calculated from the Equation 4.1. Where V is the internal volume of the mould.

$$\rho = \frac{m_2 - m_1}{V} \tag{4.1}$$

The dry density ρ_d of each compacted specimen was calculated from Equation 4.2. Where w is average moisture content. The dry densities against the corresponding moisture contents were plotted.

$$\rho_d = \frac{100p}{100+w} \tag{4.2}$$

4.4.3 Determination of dry moisture content of soil

Naturally, soil contains some amount of water. The amount of water in the soil is expressed as a proportion by mass of the dry particles, which is known as moisture content. The test was carried out to determine the dry moisture content of the soil before used. The test was conducted in accordance with British Standards Institute BS 1377:2 (1990). It adopted the oven-drying method. The main apparatus used include drying oven, a balance, corrosion-resistant container and a scoop.

Corrosion-resistant container was cleaned and weighed (m_1). A sample of soil was taken, crumbed and placed loosely in the container. The weight of the container and the sample was taken (m_2). The container and its content were placed in a drying oven at a temperature of 105 °C to dry (Figure 4.4). The sample was considered dried when the difference in the successive weights of the cooled sample at interval of 4 hrs after 24 hr did not exceed 0.1%. After drying, the container and its content was weighed (m_3). The moisture content of the specimen (MC) was calculated as percentage of the dry soil mass from the Equation 4.3.

$$MC = \frac{m_2 - m_3}{m_3 - m_1} \times 100 \qquad (4.3)$$

Figure 4.4: Drying of soil samples

4.4.4 Determination of Atterberg limits

The Atterberg tests were performed to determine the plasticity of the soil samples used for making the enhanced soil blocks. The Atterberg tests provided the Liquid limit, Plastic limit and later calculated the Plasticity Index of the samples in accordance with British Standards Institute BS 1377:2 (1990).

4.4.4.1 Liquid limit

According to British Standards Institute BS 1377:2 (1990), the liquid limit is the empirically established moisture content at which a soil passes from the liquid state to the plastic state. It provides a means of classifying a soil, especially when the plastic limit is also known. The cone penetrometer method was adopted because it is easier to perform and gives more reproducible results than the Casagrande method. The main apparatus used are spatulas, drying oven, weighing balance, flat glass plate, a penetrometer (with an angle of 30 ± 1°) and a corrosion-resistant container.

A sample weighing 1500 g was taken from the material and sieved through 425 µm BS test sieve. The sample was placed on the flat glass plate and mixed thoroughly with distilled water using the spatula until the mass became thick and homogeneous paste such that the first cone penetration reading was about 15 mm. A portion of the paste was pushed into a cup with spatula making sure no air was trapped. The cup containing the paste was placed in position under the cone, then the cone was released for a period of 5 seconds into the paste and the dial gauge lowered to contact the cone shaft for the reading to be taken. A little distilled water was added and the procedure repeated such that a range of penetration values were between 15 mm and 25 mm by the entire test. The moisture content corresponding to a cone penetration of 20 mm to the nearest whole number was reported as the liquid limit.

4.4.4.2 Plastic limit test

According British Standards Institute BS 1377:2 (1990), the plastic limit is the empirically established lowest moisture content at which a soil becomes too dry to become plastic. The plasticity limit (w_p) provides a means of classifying cohesive soils. It is used, together with the liquid limit to determine the plastic index. The main apparatus used include spatulas, apparatus for moisture content and a rod (3 mm diameter and 100 mm long).

20 g sample of soil mixed with distilled water was allowed to dry partially until it became plastic enough to be shaped into a ball. The soil was moulded into balls between the fingers and rolled between the palms of the hands. The sample was then divided into two of about

10 g each. Each sub-sample was divided into four more equal parts and each part was moulded in the finger to form threads of about 6 mm long and approximately 3 mm in diameter. The moisture contents of each of the sample was then determined by keeping pieces of the thread in moisture cans and oven dried and the plasticity limit determined.

4.4.4.3 Plasticity Index

The plasticity index (I_p) was determined by the help of the liquid limit (w_L) and plastic limit (w_p) from the Equation 4.4.

$$Ip = w_L - w_p \tag{4.4}$$

4.4.5 Determination of chemical composition/element/oxides in soil samples

This test was conducted to determine the chemical composition/element/oxides and other characteristics such as acidity (pH) level of the soil samples that were used for making the enhanced soil blocks. These properties of soil have chemical effect such as efflorescence on soil blocks for construction purposes. Due to unavailability of X-ray Fluorescence (XRF) analyser in the laboratory where testing was done in Ghana, water-based extraction (leaching) procedure was used for providing information on the soluble components. The test analysis was performed using (1) inductively coupled plasma-atomic emission spectrometry (ICP-MS) method, (2) Palintest method for the elements that the ICP-MS could not detect, and (3) pH meter measurement.

4.4.5.1 ICP-MS analysis/Palintest

The available nutrients and heavy metal concentrations in the soil were determined through water-base extraction. The soil samples were subjected to extraction of key components with distilled water. Samples of 10 g were placed in Whatman Vecta Spin 20 polypropylene centrifuge tubes with the 0.2 pm pre-filter provided. 30 ml of distilled water was added to each tube. The tubes were then placed in a Stuart SSL1 orbital shaker and shaken at 200 rev min^{-1} for 1 hr. The tubes were then centrifuged (Sigma 6K15) at 4000 rev min^{-1} for 15 min. The resulting filtered extracts were decanted and stored in bottles at 4°C to await analysis.

The analyses of the filtrates obtained were performed by ICP-MS (Agilent 7500ce ICP-MS) in accordance with British Standard Institute BS EN ISO 17294:1 (2006). Other elements/oxides were determined by the use of Palintest

4.4.5.2 pH level

The pH measurements were made in accordance with the guideline of British Standard (British Standard Institute BS EN 13037, 2011). A JENWAY pH Meter 3305 (range 0.0 to 14.0 pH with an accuracy ± 0.2 pH) was used to record pH of the soil samples. Prior to recording each reading, the meter was calibrated, using pH buffer 7 and EC 1413 µS/cm solutions. In order to determine the pH of the soil samples, a 30 g representative sample was collected and placed in 150 ml of deionised water. After stirring in the aqueous suspension for 1 minute, the meter was inserted and the pH of the soil samples were observed and recorded after the readings had stabilised (Figure 4.5).

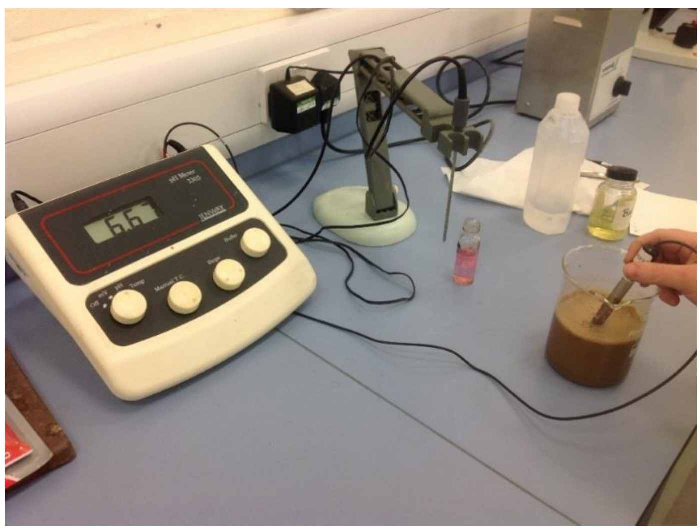


Figure 4.5: Determining pH of the soil samples

4.5 RESULTS AND ANALYSIS

4.5.1 Optimum moisture content and maximum dry density

The optimum moisture content and maximum dry density of the soil samples are presented in Figure 4.6 as obtained from the compaction test. The result indicates that the OMC for soil B is 17.59% by weight of soil for a MDD of 1.779 Mg/m^3, for soil R the optimum moisture content is 19.02% by weight of soil for a maximum dry density of 1.791 Mg/m^3, while soil HI is 11.9% optimum moisture content with 1.835 Mg/m^3 a maximum dry density. The details of the test results could be found in Appendix A.

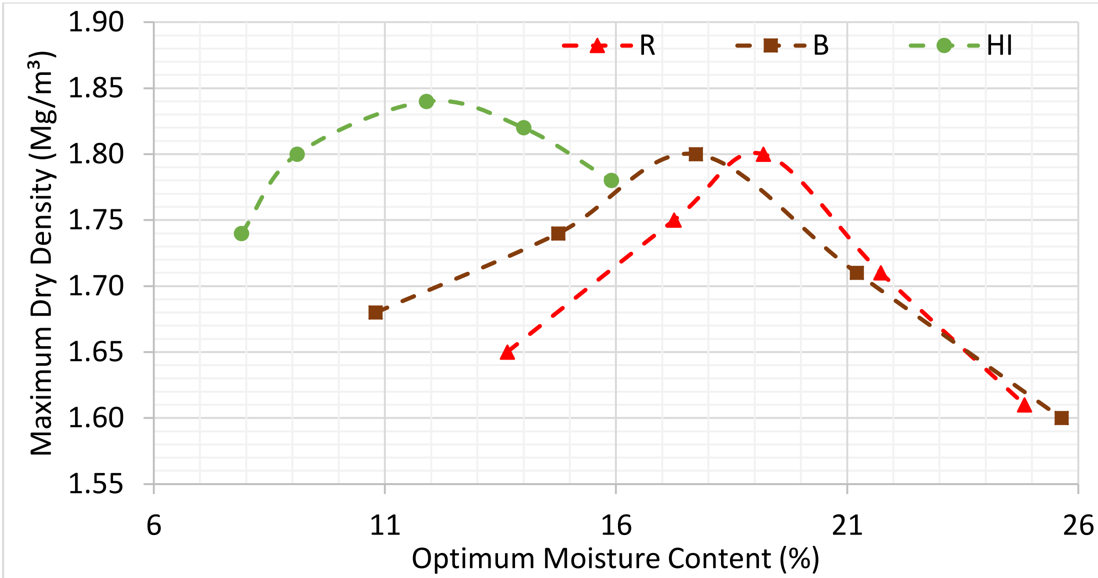


Figure 4.6: Compaction test result

The results show that soil HI recorded the lowest OMC and highest MDD as compared to soil R and soil B, while the OMC and MDD of soil R were more than soil B. The MDD results obtained can be compared with the results of previous studies (Alavéz-Ramírez et al., 2012, Bahar et al., 2004, Cai et al., 2006, Yalley and Kwan, 2008). However, the OMC result of soil R and B were higher than the above previous studies (Table 4.1). This might be due to the lower dry moisture content of the soil samples, and therefore required higher moisture to reach the maximum dry density. On the other hand the result of the soil used in a study by Degirmenci (2008) recorded a very high OMC (37.7%) as compared with the current study soil samples. The OMC obtained were used as water content for making the soil blocks.

Table 4.1: Experimental soils OMC and MDD compared with previous studies

Reference	OMC (%)	MDD (Mg/m^3)
Alavéz-Ramírez et al. (2012)	9.4	1.98
Bahar et al. (2004)	11.0	1.76
Cai et al. (2006)	15.8	1.70
Yalley and Kwan (2008)	12.0	1.76
Degirmenci (2008)	37.7	13.64
Current study (soil R)	19.0	1.79
(soil B)	17.6	1.78
(soil HI)	11.9	1.84

4.5.2 Particle size distribution

Sieve analyses and sedimentation by hydrometer method were used to determine the particle size distribution of the soil samples. Appendix B provides details of the test results. The results of the particle size distribution (grading) of the experimental soils are presented in Figure 4.7, with the lower and upper limits usually recommended for soil blocks (Houben and Guillaud, 1994). The results indicate that soil B and soil HI are within the limits, while soil R is lies partially outside the limits.

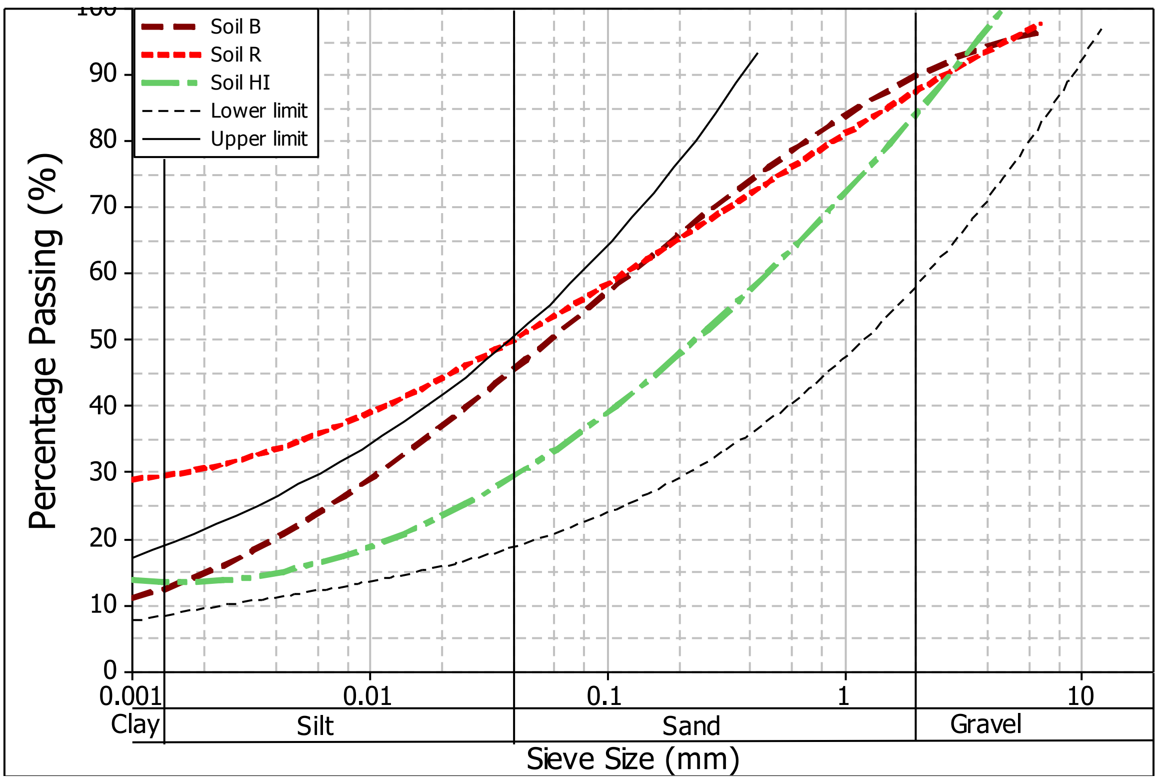


Figure 4.7: Grading test results

From the grading test results, the clay content is 12% for soil B, 30% for soil R and 14% for soil HI. The silt content is 28% for soil B and 16% for soils R and HI. The sand content is 46% for soil B, 39% for soil R and 64% for soil HI. And the gravel content is 12% for soil B, 15% for soil R and 8% for soil HI.

Notable in the current result are the gravel and the clay contents. Some soils used in previous studies (Alavéz-Ramírez et al., 2012, Cai et al., 2006, Degirmenci, 2008) had a very low and some 0% gravel content (see Table 3.9 under Section 3.3.2) as compared to the current study's soils. The clay content in soil R was above the recommended content by Houben and Guillaud (1994), similar clay content were obtained in some previous studies (Binici et al., 2005, Galán-Marín et al., 2010) (see Table 3.9 under Section 3.3.2).

4.5.3 Dry moisture content

Table 4.2 presents the summary results of the moisture content of the soil samples before used for making blocks. The details of the results can be found in the Appendix D. The results show that soil B contained natural moisture content of 9.4%, soil R contained natural moisture content 10.3% and soil HI had moisture content 8.7%.

Table 4.2: Results of moisture content

Soil Sample	**Moisture content (%)**		
	Mean	**Std Dev**	**Anderson-Darling Normality (*p*-value)**
Soil B	9.4	0.6	0.055
Soil R	10.3	0.5	0.303
Soil HI	8.7	0.4	0.520

Five replicates for each soil sample

4.5.4 Atterberg limits

The details of the Atterberg limits test results can be found in Appendix C. The importance of I_p, w_p and w_L to the strength properties of stabilised soil blocks has been reported in previous studies (Bryan, 1988, Walker, 1995), see more details in Section 2.5.5. The Atterberg limits test results are presented in Table 4.3.

Table 4.3: Atterberg limits test results

Soil type	**Liquid limit (%)**	**Plastic limit (%)**	**Plasticity index (%)**
Soil B	31.1	17.2	13.9
Soil R	51.2	27.3	23.9
Soil HI	31.7	18.0	13.7

Figure 4.8 shows the plasticity chart for the soil classification. The results indicate that soils B and HI are low plasticity clay (CL) soils and soil R is high plasticity clay (CH) soil (British Standard Institute BS 5930, 2015). The results are in agreement with the clay content of the soil types obtained in the PSD test results in Section 4.5.2. The result obtained by soils B and HI can be compared with the results from previous studies (Aymerich et al., 2012, Bouhicha et al., 2005, Cai et al., 2006, Egenti et al., 2014). For soil R, similar result was reported in the other studies (Chan, 2011, Elenga et al., 2011) (see Table 3.10 under Section 3.3.2).

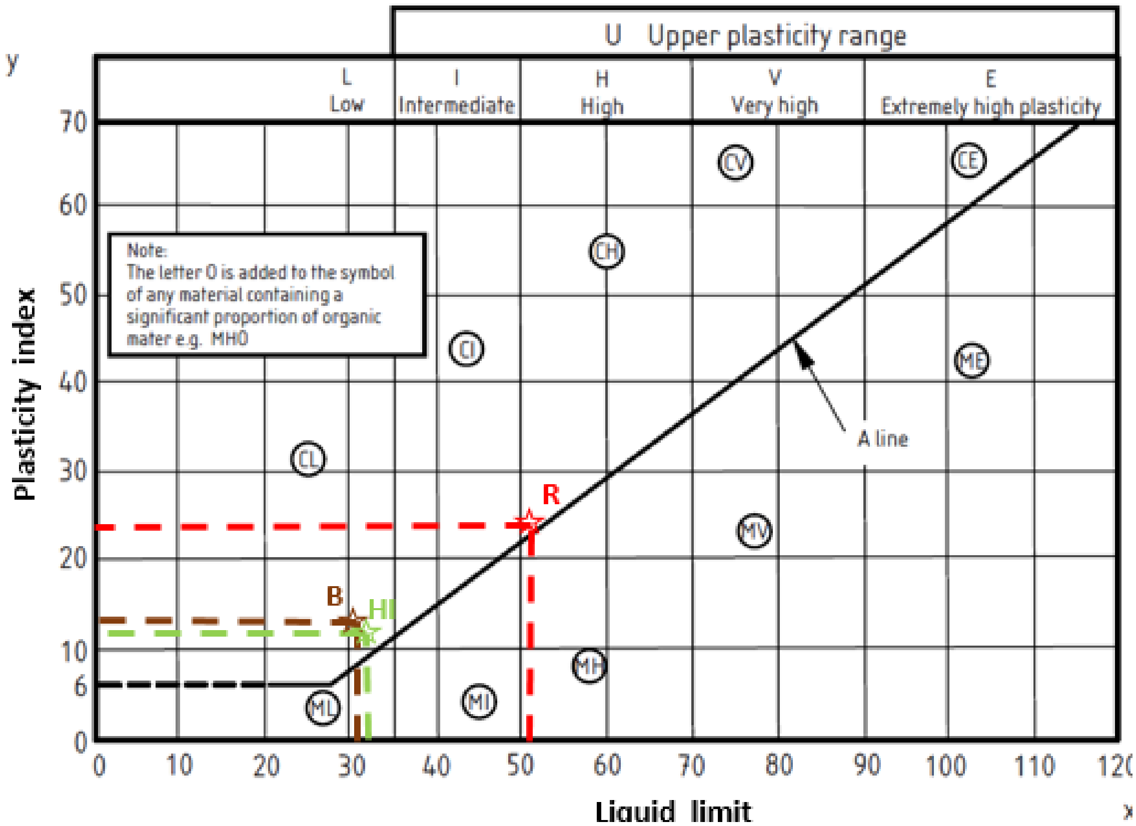


Figure 4.8: Plasticity chart for classification of soil
(British Standard Institute BS 5930, 2015)

The plasticity limits of 13.9, 23.9 and 13.7, respectively for soils B, R and HI are within the limits of 7 to 29 recommended by Doat et al. (1979) for cement stabilised soil. It must be noted that no recommendation has been made for fibre reinforced soil.

4.5.5 Soil chemical composition/element/oxides

The chemical properties of the soils samples based on the soluble components are presented in Table 4.4. The result shows that calcium (Ca), chloride (Cl^-), sulphate (SO_4^{2-}) and magnesium (Mg) were the element and compound with high concentrations for soils R and B, while silica (SiO_2), chloride (Cl^-), magnesium (Mg) and calcium (Ca) were the element and compound with high concentrations for soil HI. The main difference between the Ghana soils (R and B) and UK soil (HI) was the amount of Ca and SiO_2 concentrations. Soils R and B had a high Ca (65 and 44 mg/l, respectively) as compared to soil HI (5.68 mg/l), while soil HI had a very high SiO_2 (76.62 mg/l) than soils R and B (0.08 and 0.06 mg/l, respectively). This might be due to the different deposition of minerals of the different locations where the soil samples were obtained.

Table 4.4: Chemical composition/element/compound of soluble extract of soils

Element/compound concentration	**Soil B (mg/l)**	**Soil R (mg/l)**	**Soil HI (mg/l)**
Aluminum (Al)	0.06	0.09	2.84
Calcium (Ca)	44.00	65.00	5.68
Silica (SiO_2)	0.06	0.08	76.62
Potassium (K)	3.88	4.19	2.40
Zinc (Zn)	0.86	0.91	0.31
Lead (Pb)	0.10	0.15	4.47
Iron (Fe)	1.038	1.047	2.36
Magnesium (Mg)	14.80	15.80	10.50
Chloride (Cl^-)	18.99	31.49	9.00
Phosphate (PO_4^{3-})	6.17	3.09	0.15
Sulphate (SO_4^{2-})	20.00	28.00	3.00

The results of pH are reported in Table 4.5. This means all the soils are classified as close to neutral (between acidic and alkaline) according to Soil survey division staff 'Soil survey manual' (1993). This means the experimental soils did not contain soluble substance that may affect their behaviour. The values obtained in the present study are lower that the value (9.69) obtained in the study by Jafari and Esna-ashari (2012).

Table 4.5: Soil samples pH

Sample	**pH**	**Soil type**
B	7.33	Neutral
R	7.44	Neutral
HI	6.67	Slightly alkaline

4.6 SUMMARY

Table 4.6 summarises the values obtained in investigating the properties of the three main soil types used in the study. It consisted of the types of soil samples, preparation of the soil samples, methods of determining the soil properties and results and analysis. The test conducted include compaction, particle size distribution, dry moisture content, Atterberg limits and chemical composition.

Table 4.6: Properties soil samples

Properties	Soil sample		
	B	R	HI
Proctor test			
Optimum moisture content (%)	17.95	19.02	11.80
Maximum dry density (Mg/m^3)	1.779	1.791	1.83
Atterberg limits			
Liquid limit w_L (%)	31.1	51.2	18.0
Plastic limit w_p (%)	17.2	27.3	31.7
Plasticity index Ip (%)	13.9	23.9	13.7
Soil classification			
USCS	CL	CH	CL
Particle size distribution			
Gravel (>2 mm) (%)	12	15	8
Sand (2 - 0.063 mm) (%)	46	39	64
Silt (0.063 - 0.002 mm) (%)	28	16	16
Clay (<0.002 mm) (%)	14	30	12
Natural moisture content			
Content (%)	9.4	10.3	8.7
pH			
Value	7.33	7.44	6.66
Element/compound (mg/l)			
Al	0.06	0.09	2.84
Ca	44.00	65.00	5.68
SiO_2	0.06	0.08	76.62
K	3.88	4.19	2.40
Zn	0.86	0.91	0.31
Pb	0.10	0.15	4.47
Fe	1.04	1.05	2.36
Mg	14.80	15.80	10.50
Cl^-	18.99	31.49	9.00
PO_4^{3-}	6.17	3.09	0.15
SO_4^{2-}	20.00	28.00	3.00

The main conclusion of the investigation can be found in Section 12.2. The following findings can be summarised:

1. Soil B was a low plasticity clay soil, had 44 mg/l calcium as the highest chemical composition, had a close to neutral pH value (7.33) and was within the limits for soil suitability for earth block construction. From these characteristics, soil B was found to be good enough to be used as soil matrix for making enhanced soil blocks.
2. Soil R was a high plasticity clay soil, obtained 65 mg/l calcium as the highest chemical composition, had a close neutral pH value (7.44) and was partially outside the limits of clay content for soil suitability for earth block construction. From these characteristics, soil R was found to be somewhat good for making enhanced soil blocks.
3. Soil HI was also a low plasticity clay soil, recorded about 77 mg/l silica as the highest chemical composition, had a close to neutral pH value (6.67) and was within the limits for soil suitability for earth block construction. From these characteristics, soil HI was also found to be good to be used as soil matrix for making enhanced soil blocks.

CHAPTER 5

5 PROPERTIES OF AGRICULTURAL WASTE FIBRES

5.1 INTRODUCTION

The aim of this chapter is to determine the characteristics of the agricultural waste fibres that were used for making the enhanced soil blocks. The chapter consists mainly of agricultural waste fibres, preparation of agricultural wastes fibres, methods of determining the fibres properties, results and analysis.

5.2 AGRICULTURAL WASTE FIBRES

Fibres obtained from three different agricultural wastes (sugarcane residue ‘bagasse’, coconut husk and oil palm fruit residue) were used for the study. These were selected because they are among the common agricultural wastes generated in Ghana. These wastes are usually burnt which pollutes the air and affect the health of the general public.

The waste fibres have been selected as they cover a wide range of properties, and are also abundant agricultural waste materials in West Africa. They are not the only wastes in the study location from which their fibres can be used. There are other waste from agriculture products such as bamboo, sisal and rice husk which are also available. However, lack of clear methodological process of extracting the fibres, the low scale production in the study location and limited time frame resulted in their exclusion from the study. See Section 2.6.3 for more information on the types of agricultural waste fibres.

5.3 PREPARATION OF AGRICULTURAL WASTE FIBRES

The agricultural wastes were processed to obtain their fibres. The fibres were prepared through different, but similar processes for each type. The processes have been described below.

5.3.1 Bagasse fibres

Bagasse fibres used in the study were obtained from sugarcane residue at a local sugarcane alcohol distillery mill in Somanya, Ghana (Figure 4.10a). The juice (liquid) from the sugarcane had been extracted for producing alcoholic drink leaving the residue (bagasse). The sugarcane residue was already crushed (Figure 4.10b) at different sizes through the alcohol extraction process. It was soaked in water for 48 hr, and then cut at their joint at smaller sizes and beaten manually on wooden surface with a wooden bar of 80 mm diameter and 450 mm length until the fibres were exposed. The fibres were then separated from the pith particles and washed in water. The fibres were spread out in the sun for a period of two weeks to dry (Figure 4.10c). To assure a uniform drying process the layer of bagasse fibre was turned over once a day.

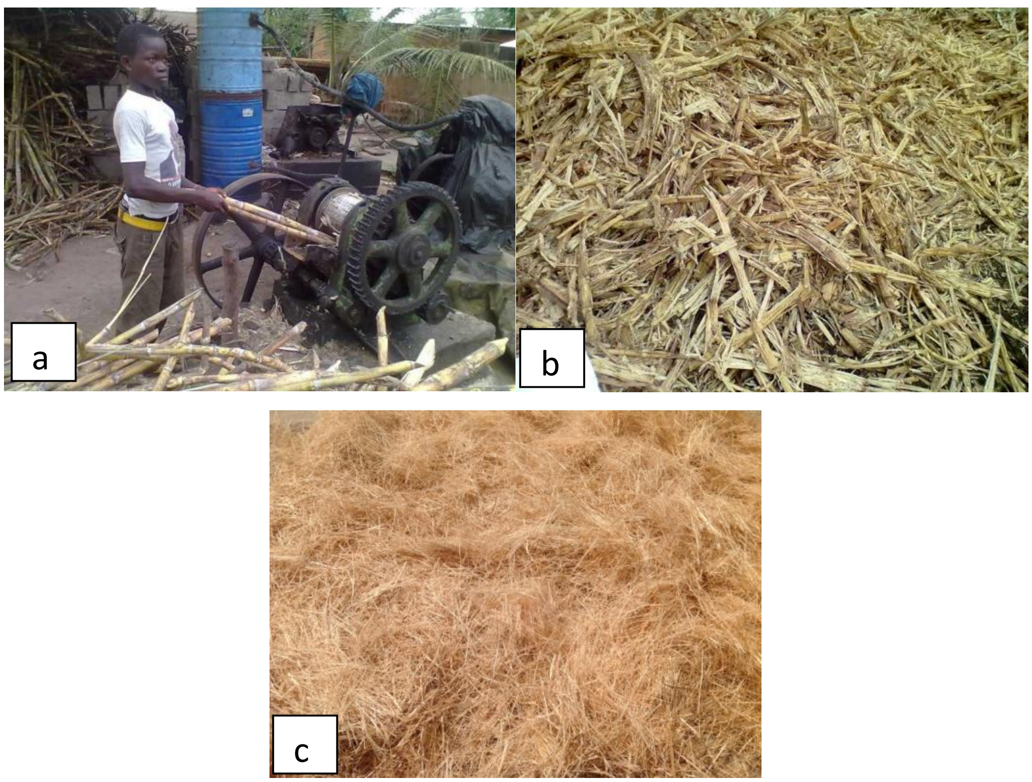


Figure 5.1: Preparation of bagasse fibre
(a) Extraction of juice from sugarcane; (b) sugarcane residue; (c) bagasse fibres extracted

5.3.2 Coconut fibres

Coconut fibres were obtained from the husk of coconut fruit. They are the fibrous material found between the internal shell and the outer coat of a coconut fruit. The coconut husks were obtained from coconut vending points at Cape Coast in Ghana. After the juice (water) and the food were consumed from the coconut fruit, the vendors collect the husks with the internal shells as waste to dispose them by throwing away or burning. The wastes were collected, and the shells removed, leaving the fibrous husks (Figure 4.11a). The fibrous husks were soaked in water for 48 hr and beaten with wooden bar on wooden surface to expose the fibres. The fibres were then separated from the pith particles and washed. The fibres were dried (Figure 4.11b) under the sun for two weeks, turning it over each day to ensure uniform drying.

Figure 5.2: Preparation of coconut fibre
(a) Coconut husks, (b) coconut husk fibres

5.3.3 Oil palm fruit fibres

Oil palm fruit fibres were obtained from palm oil extraction plant in Kumasi, Ghana. The fruits were crushed and the oil extracted, leaving the fibres and the shells as waste to be thrown away or burned. These wastes were collected, and the fibres were separated from the shells. The fibres were washed in warm water to remove any oil content left in them. They were then dried in the sun (Figure 5.3) for two weeks.

Figure 5.3: Drying of oil palm fruit fibres

5.4 METHODS FOR DETERMINING FIBRES PROPERTIES

The fibres were examined to determine their physical and mechanical properties. The physical properties tests included fibre length and diameter, moisture content, density and water absorption. The mechanical properties tests adopted tensile strength test of fibres. The tests were modified from the methodological approach of Ghavami et al. (1999), because it provided detailed information on determining the properties of natural fibres such as bamboo, sisal and coconut.

5.4.1 Lengths and diameters of fibres

The lengths of the fibres were measured with a steel rule. The fibres were straightened on steel rule for which their length were measured. One hundred specimens (the same used for diameter measurement) from each fibre type were used. After that the mean, standard deviation and relative standard deviation (RSD) of each type of fibre were determined after normality tests were conducted with Minitab 16 statistical software.

These fibres were obtained from Ghana and the measurements were conducted at University of Portsmouth, UK. The fibres were measured at five different points along the length due to irregular shape of the fibres for their mean and distribution diameters to be determined.

A compound light Microscope (Leitz HM-LUX3) of 10x magnification with graticule eye piece was used for measurement (Figure 5.4a). The eyepiece graticule which is located at the primary image of the microscope was focused on the fibre (Figure 5.4b). The fibre was superimposed on the slide for 0.1mm ÷ objective magnification. Typically this gives the 0.01mm per division at 10x. The diameters of the fibres were checked by calibrating the eyepiece using a stage micrometre.

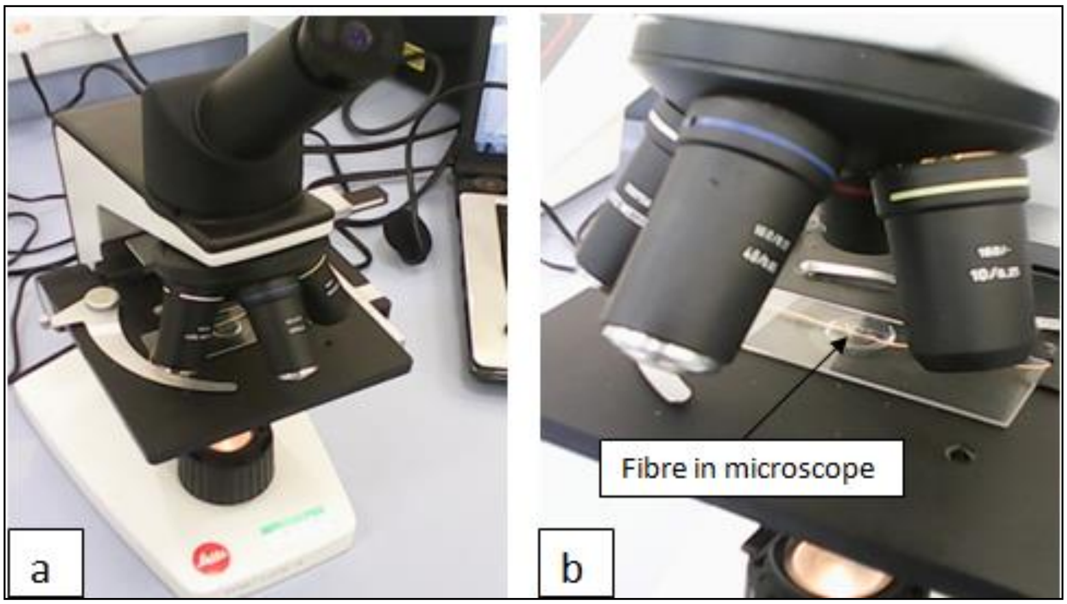


Figure 5.4: Determining fibre diameter with Leitz HM-LUX3 microscope

5.4.2 Dry moisture content and specific weight

The dry moisture content was determined by using three bundles of each fibre type, which were first air-dried and the weight measured with electronic balance as P_d, then the same fibres were oven-dried at temperature 105 ^{O}C for 24 hrs and the weights measure as P_o. The moisture content (MC) was then calculated by the Equation 5.1.

$$MC = \frac{P_d - P_o}{P_o} \times 100 \qquad (5.1)$$

In determining the specific weight (γ), three bundles of each fibre type were air-dried and the weight measured with electronic balance as P_d. The volumes of the displaced water after immersion of fibres for 24 hrs were measured as V (Figure 5.5). The specific weight was calculated using the Equation 5.2.

$$\gamma = \frac{P_d}{V} \tag{5.2}$$

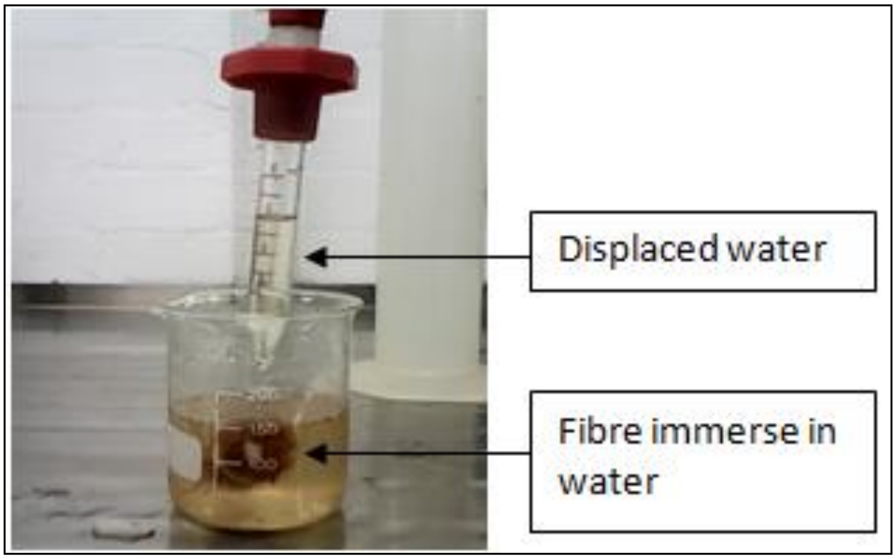


Figure 5.5: Determining the volume of fibres

The mean, standard deviation and RSD of each fibre type results were determined after normality tests were conducted.

5.4.3 Water absorption for 14 days

The water absorption of the fibres was determined by air-drying three bundles of each fibre type and their weights measured (P_d), then the fibres were soaked in water their weights measured (P_h) at 24 hrs intervals for 14 days. The water absorption (W) of the fibres was calculated by the Equation 5.3.

$$W = \frac{P_h - P_d}{P_d} \times 100 \tag{5.3}$$

5.4.4 Tensile strength and modulus of elasticity

The tensile strength test was conducted on dried and wet fibres. For the wet sample, randomly selected fibres were kept in: (1) water, and (2) damp tissue for which tests were done at 30 days intervals for 120 days. The tests were carried out in a testing machine “Tinius Olsen

H50KS" (Figure 5.6a) with a maximum capacity of 50 KN. Each fibre was held in the test machine and load applied (Figure 5.6b) starting from 50 N and at speed of 1 mm/min which continued until the fibres failed. The maximum load at which the fibres failed was recorded and the tensile strength calculated.

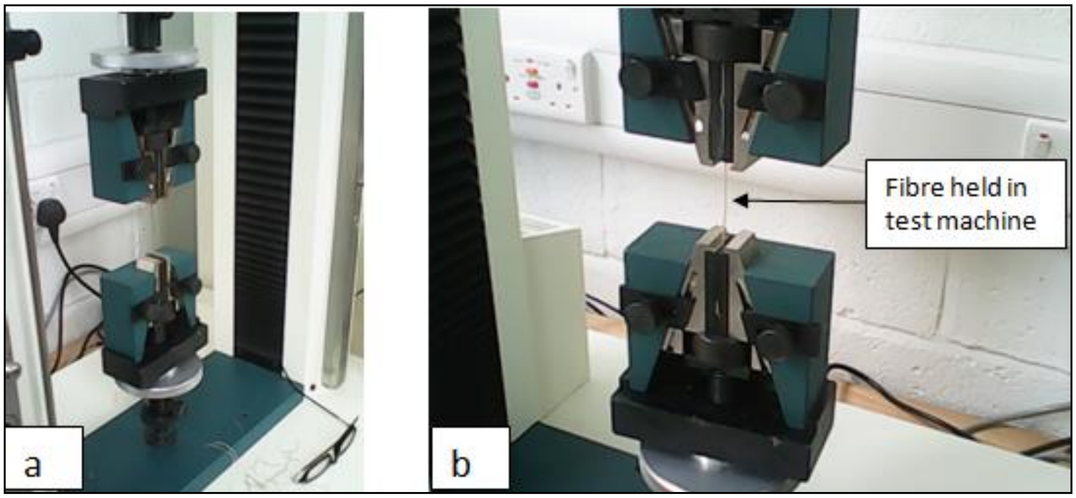


Figure 5.6: Determining tensile strength of fibres using Tinius Olsen H50KS
(a) Test set-up, (2) fibre held in machine under tensile stress

After the tensile strengths tests were carried out (Figure 5.6), the maximum load (*N*) and distance (*mm*) at which the fibre failed were recorded for which the tensile stress (σ) and tensile strain (ε) were calculated. After, the modulus of elasticity (E) of the fibres were calculated using the Equation 5.4.

$$E = \frac{\sigma}{\varepsilon} \qquad (5.4)$$

The mean, standard deviation and RSD of each fibre type results were determined after normality tests were conducted.

5.4.5 Scanning Electron Microscopy (SEM) analysis

SEM images of single fibre were taken with JSM-6100 scanning microscope at 35x and 500x magnification for each fibre type to show the texture of the fibres.

5.5 RESULTS AND ANALYSIS

The properties of natural fibres are affected by natural variability and environmental conditions (Ghavami et al., 1999). Therefore a number of tests are required in order to determine the properties of any fibre type. The results are based on single a fibre test conducted on all the fibre types instead of twist, bundle or rope.

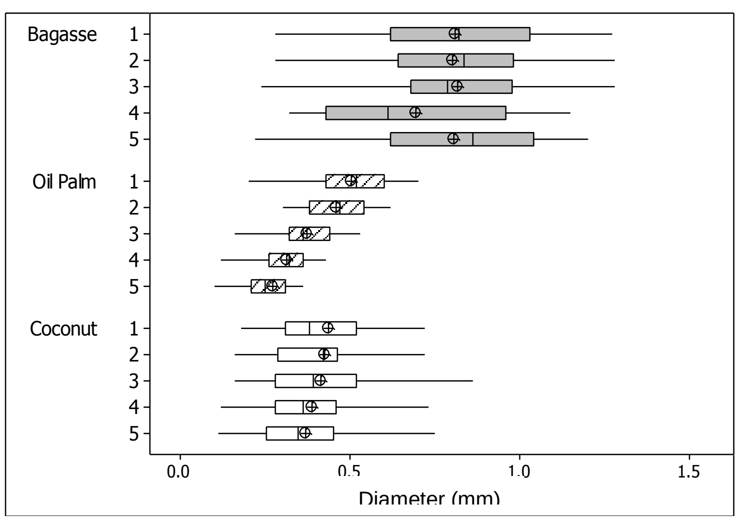
5.5.1 Lengths and diameters of fibres

Table 5.1 presents the summary of the results obtained from laboratory tests performed on the lengths and diameters of coconut, oil palm and bagasse fibres.

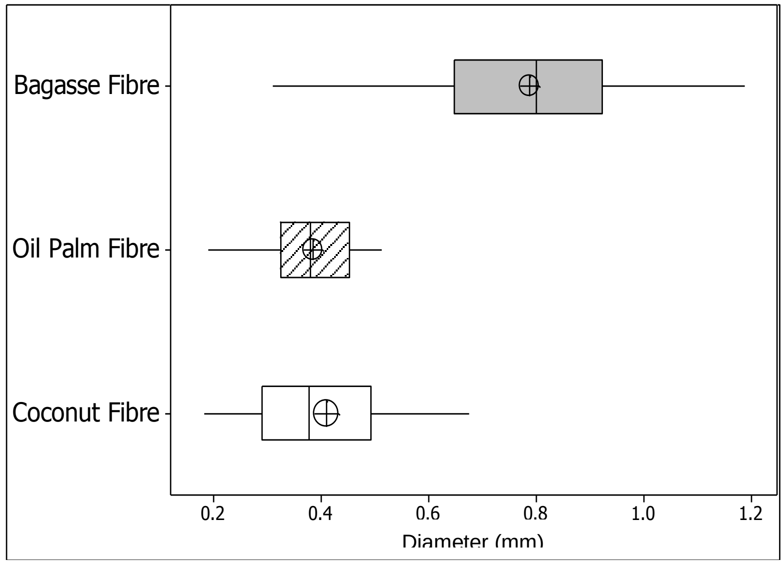
Table 5.1: Lengths and diameters of fibres

Fibre	Length (mm)				Diameter (mm)			
	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)
Bagasse	110	28	26	0.056	0.78	0.19	23	0.270
Oil palm	38	6	17	0.136	0.38	0.08	23	0.075
Coconut	103	17	17	0.112	0.40	0.17	42	0.065

Bagasse fibre recorded the highest average length and diameter while oil palm fibre had the least. The distribution of the measurements are shown in Figures 5.7 and 5.8 respectively for diameter and length. They display a generally normal distribution with only the oil palm diameter showing a marked tapering.



(a)



(b)

Figure 5.7: Distribution of fibre diameter measurements: (a) five points, (b) mean
Box plots represent the inter-quartile range of fibre diameter

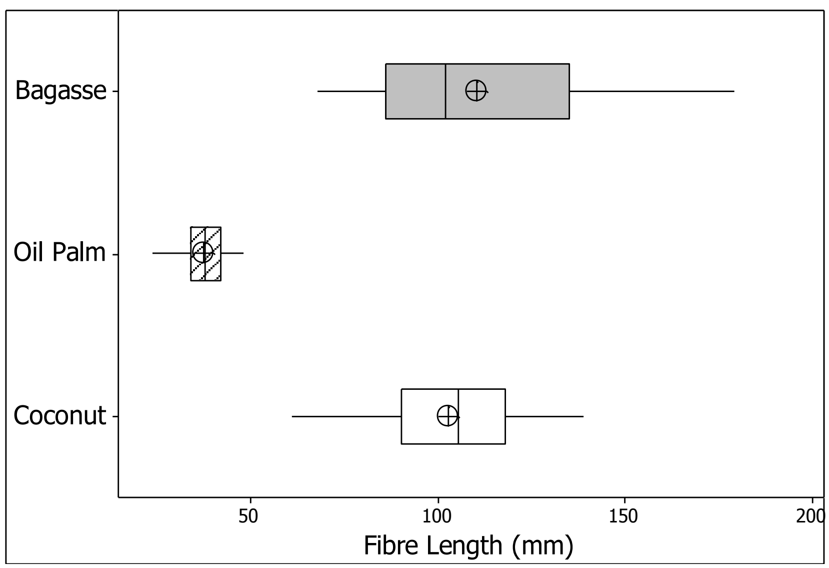


Figure 5.8: Distribution of fibre length measurements
Box plots represent the inter-quartile range of fibre length

The fibres lengths and diameters recorded are within the values obtained in previous studies (see Table 2.7 under Section 2.6.4).

5.5.2 Dry moisture content and specific weight

The dry moisture content and specific weight results of the fibres are presented in Table 5.2.

Table 5.2: Dry natural moisture content and specific weight

Fibre	Dry moisture content (%)				Specific weight (g/cm^3)			
	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)
Bagasse	9.7	0.4	4	0.633	0.56	0.04	7	0.398
Oil palm	7.4	0.3	4	0.264	0.77	0.03	4	0.631
Coconut	6.4	0.3	5	0.631	0.81	0.04	5	0.399

Bagasse fibre had the highest dry moisture content (9.7 %) while coconut fibre recorded the least (6.4 %). Contrarily, coconut fibre obtained the highest specific weight (0.81 g/cm^3) while bagasse fibre had the least (0.56 g/cm^3). The fibres specific weights recorded are within the values obtained in previous studies (see Table 2.7 under Section 2.6.4). The relationship between specific weight and dry moisture content of each fibre can be seen in Figure 5.9. It shows that bagasse fibre with less specific weight rather obtained a high dry moisture content, while coconut fibre with high specific weight had less dry moisture content. This means a natural fibre with less dry moisture content is likely to have a high specific weight. The distribution of the test results is shown in Figures 5.10, which display a generally normal distribution.

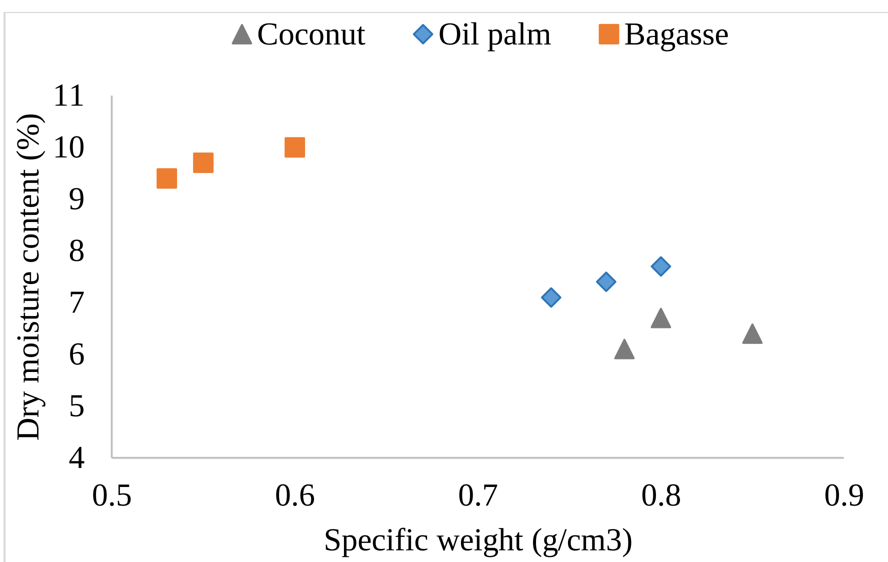


Figure 5.9: Relationship between dry moisture content and specific weight of fibres
Box plots represent the inter-quartile range of data

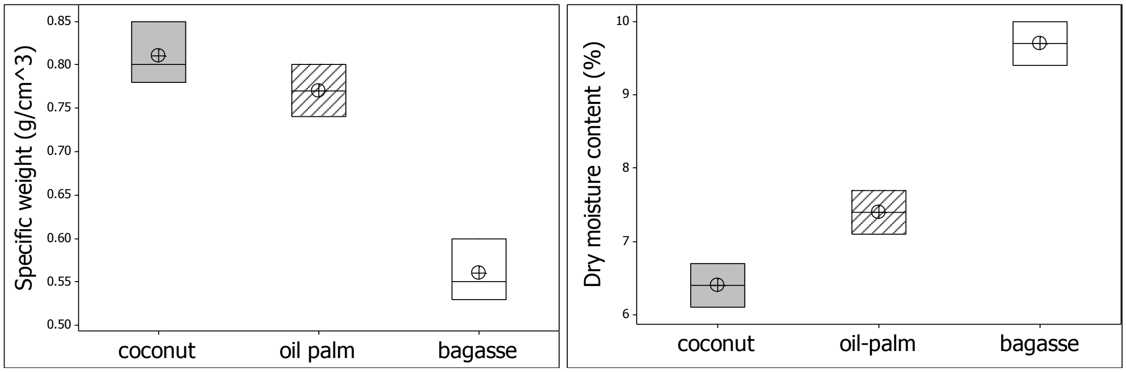


Figure 5.10: Distribution of dry moisture content and specific weight results
Box plots represent the inter-quartile range of data

5.5.3 Water absorption

The percentage water absorption of the fibres was studied for a period of 14 days. The trend of the absorption is presented in Figure 5.11. The results show that there was rapid absorption of water by all the fibre types in the first 24 hrs. The absorption continued gradually until the fourth day and then very low increase was seen until the fourteenth day, a similar trend was found in the study by Ghavami et al. (1999).

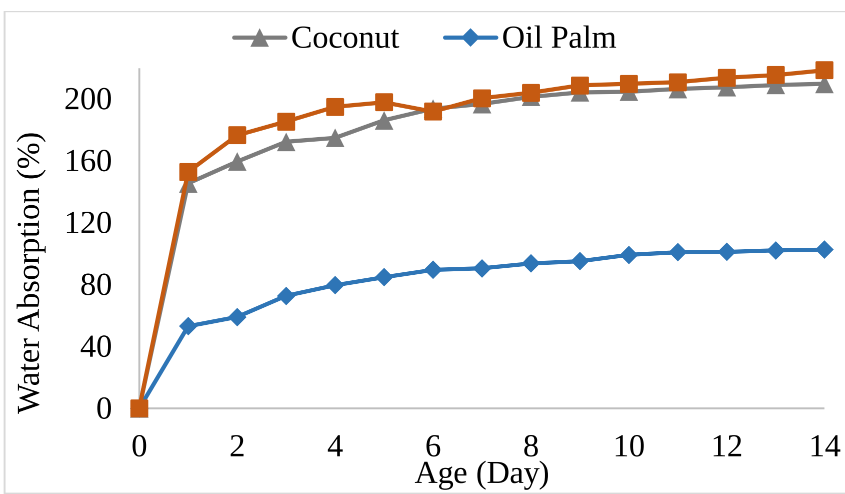


Figure 5.11: Water absorption behaviour of fibres over 14 days

Bagasse and coconut fibres recorded closely high water absorption rates, with bagasse obtained the highest, thus an increase of between 153% on the first 24 hrs and 219% on the fourteenth day. Oil palm fibre recorded the least absorption between 54% on the first 24 hrs and 103% on the fourteenth day. Study on sisal, coir and bamboo fibres by Sen and Reddy (2011) recorded similar absorption rates. However, kenaf fibres studied by Millogo et al. (2015) obtained a very high water absorption of 307% (see Table 2.7 under Section 2.6.4).

5.5.4 Tensile strength and modulus of elasticity

The results of the tensile strength and the modulus of elasticity of dry fibres are presented in Table 5.3.

Table 5.3: Tensile strength and modulus of elasticity

Fibre	Tensile strength (MPa)				Modulus of elasticity (GPa)			
	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)	Mean	Std Dev	RSD (%)	Anderson-Darling Normality (p-value)
Bagasse	42	11	26	0.875	0.89	0.22	24	0.939
Oil palm	110	21	19	0.725	0.95	0.12	12	0.638
Coconut	162	45	28	0.673	2.49	0.16	6	0.347

It shows that coconut fibre obtained the highest tensile strength and modulus of elasticity while bagasse had the least. The distribution of the test results s shown in Figures 5.12, which display a generally normal distribution. The tensile strength and modulus of elasticity results recorded are within the values obtained in previous studies (see Table 2.7 under Section 2.6.4).

Figure 5.12: Distribution of tensile strength and modulus of elasticity results
Box plots represent the inter-quartile range of data

The changes in the tensile strength of the fibres kept in water (wet) and damp tissue (damp) are reported in Figure 5.13. Day 0, on the graph represent tensile strength of the dry fibres. It can be seen that all the fibres recorded decreasing tensile strength in both wet and damp conditions over age. There was a reduction in tensile strength of about 50% for all the fibres in both damp and wet conditions at 120 days as compare to the tensile strength of dry fibres. There was slight improved tensile strength of fibres in damp condition than in wet condition for all the fibre types, however the difference between wet and damp fibres seem insignificant.

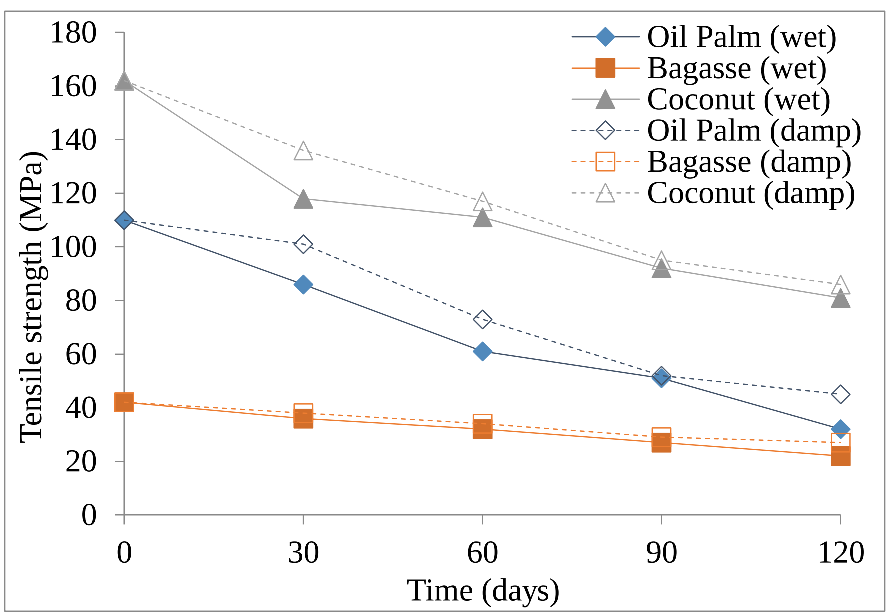


Figure 5.13: Tensile strength of fibres in damp tissue over 120 days

This implies that the tensile strength of natural fibres depreciates slightly more in water than in damp condition. There is inverse relationship between tensile strength of fibres in wet by age and the water absorption of fibre by age as shown in Figure 5.14. This means the tensile strength of the fibres decrease with increase water absorption over a period of time. A similar result was observed by Ghavami et al. (1999). This suggests that the more the fibres absorb water over a period of time the more they weaken in tensile strength, which makes them less durable. The results suggest that the tensile strength of a dry fibre is better than wet/damp fibre, implying that durability of fibres reduces in wet/damp condition over a period of time.

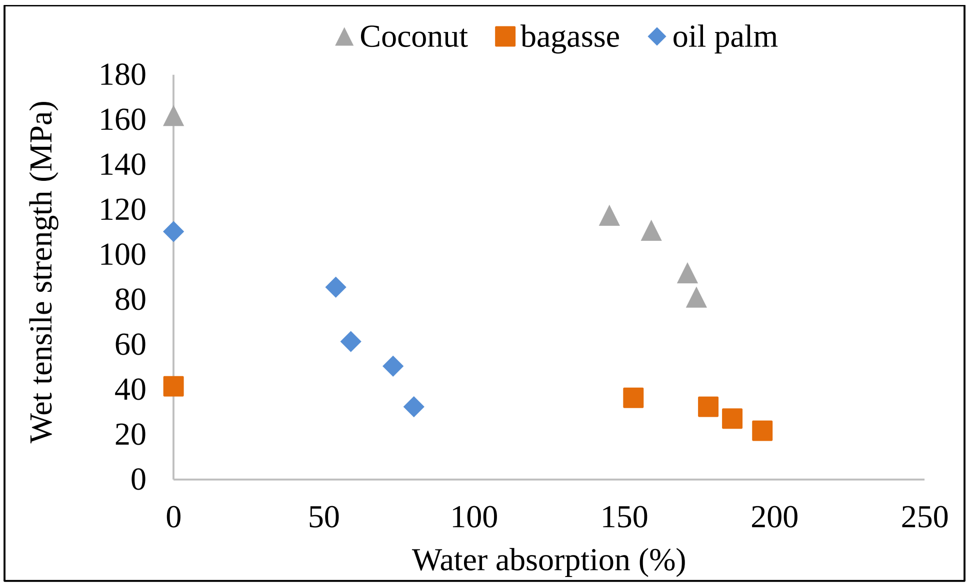


Figure 5.14: Relationship between tensile strength of wet fibres and water absorption

5.5.5 SEM of fibres

The images of the fibres and SEM results of each fibre type are shown in Figures 5.15, 5.16 and 5.17 respectively for bagasse, coconut and oil palm fibres. SEM images of single fibre were taken in 35x and 500x magnifications for each fibre type to show the texture of the fibres. As can be seen, the bagasse fibres are rougher in texture as compared to coconut and oil palm fibres. The oil palm fibres look slightly smoother than the coconut.

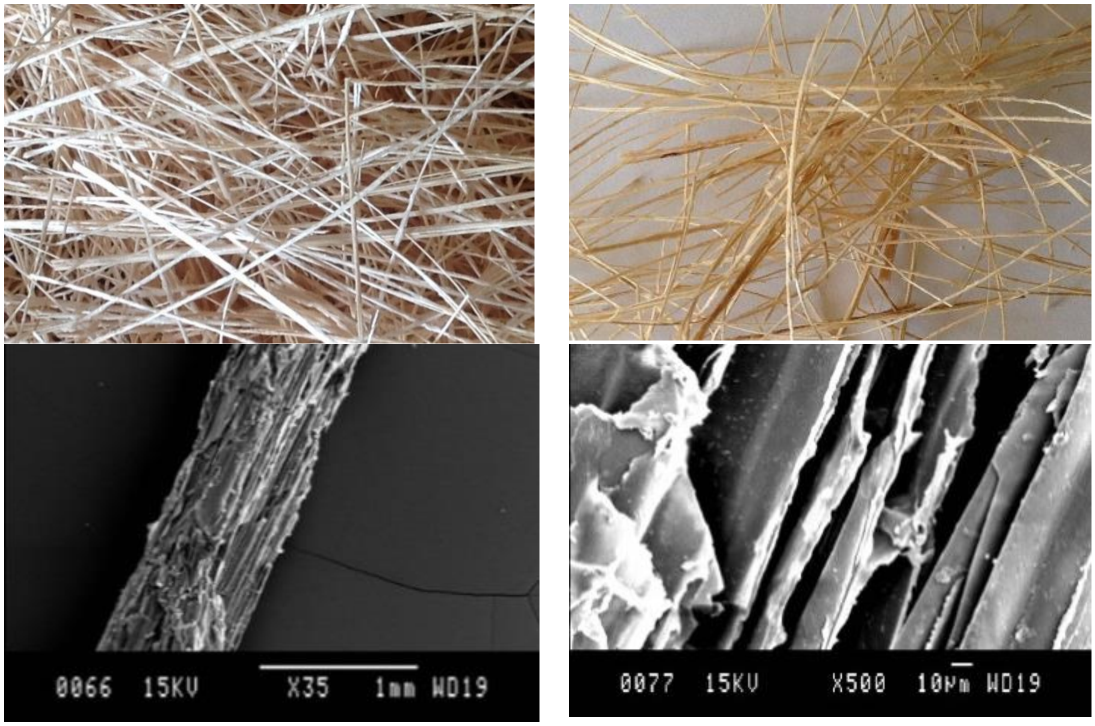


Figure 5.15: Photograph and SEM micrographs of the bagasse of fibre

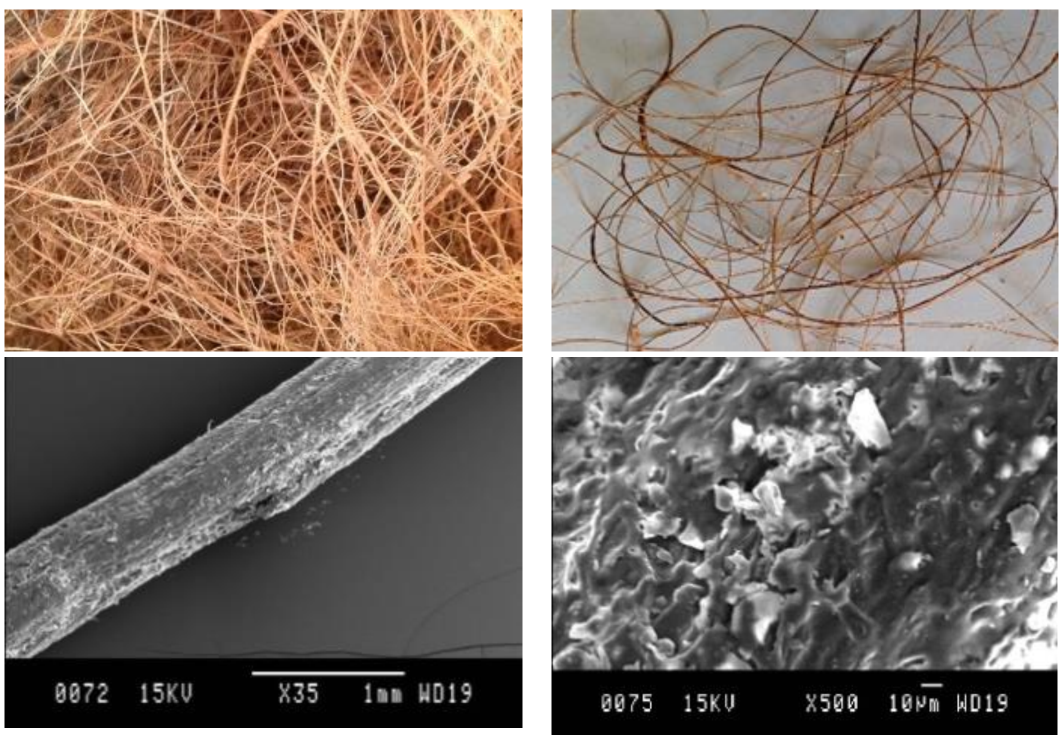


Figure 5.16: Photograph and SEM micrographs of the coconut of fibre

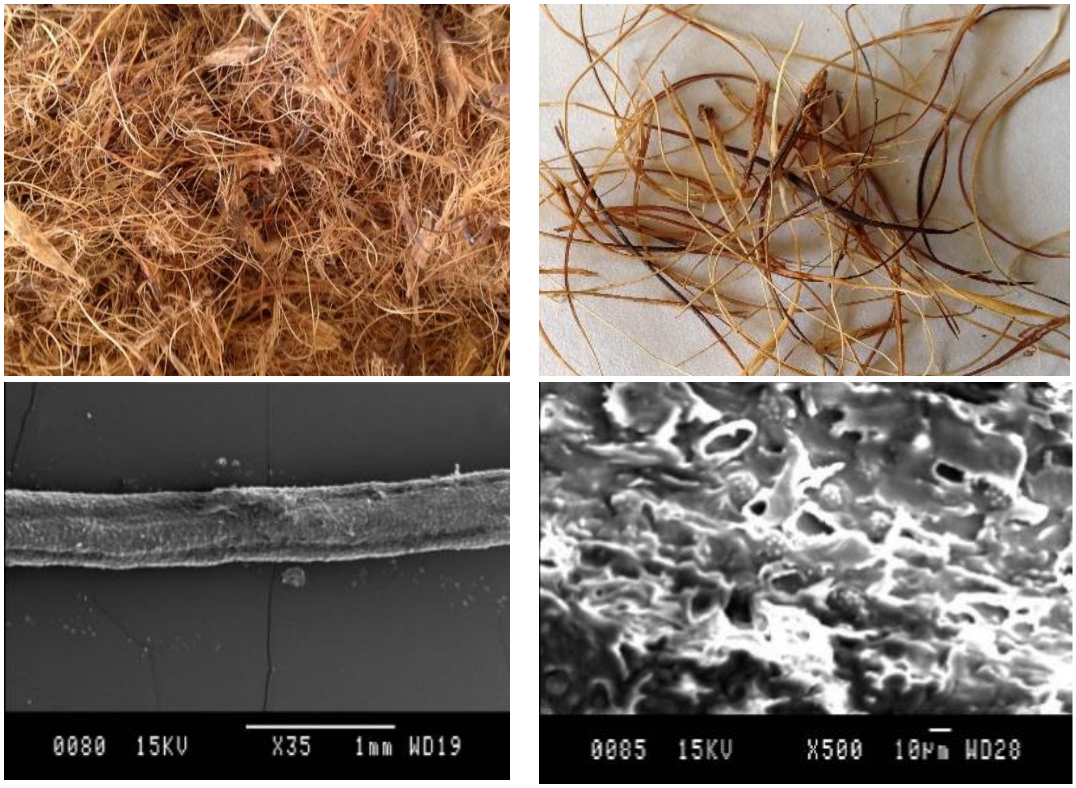


Figure 5.17: Photograph and SEM micrographs of the oil palm of fibre

5.6 SUMMARY

This chapter investigated the properties of selected agro-based fibres to be used as enhancement in soil blocks. It comprised of agricultural waste fibres, preparation of agricultural waste fibres, methods for determining fibres properties and results and analysis. Three fibre types were investigated: (1) bagasse, (2) coconut and (3) oil palm. The tests conducted include diameter, length, natural moisture content, water absorption, modulus of elasticity and SEM analysis. The results obtained are summarised in Table 5.4.

Table 5.4: Properties of experimental fibres

Property	Fibre type		
	Coconut	Oil Palm	Bagasse
Fibre form	Single	Single	Single
Texture	Smooth	Smooth	Rough
Length (mm)*	103	38	110
Diameter (mm) *	0.40	0.38	0.80
Tensile strength (MPa) *	162	110	42
Modulus of elasticity (GPa) *	2.40	0.95	0.89
Specific weight (g/cm^3) *	0.81	0.77	0.56
Natural moisture content (%)*	6.4	7.4	9.7
Water absorption (%) [a]	145 - 209	54 - 103	153 - 219

**Mean values, [a] Range values (to indicate the limits for water absorption)*

The main conclusion of the investigation can be found in Section 12.2. The following findings can be summarised:

- Different types of fibres have different dimensional properties, thus length and diameter. Bagasse fibre possessed greater dimensional properties, followed by coconut fibre and the least been oil palm fibre. The dimensional properties have influence on other properties such as water absorption and modulus of elasticity.
- Different types of fibres have different specific weight, in relation with mass and volume of the fibres. Coconut fibre achieved higher specific weight, followed by oil palm with the least been bagasse. The specific weight of the fibres have effect on the natural moisture content of the fibres, as high specific weight could lead to low dry moisture content.
- The tensile strength of dry and wet/damp fibres time differs over a period of. There was a consistent reduction in tensile strength of fibres in wet/damp condition for 120 days. However, all the fibres recoded suitable tensile strengths, as they still obtained some strength after period of time in water.
- The water absorption of fibres over a period of time differs. There was a considerable absorption in the 24 hr period, gradual increase followed until the fourth day and very little increase up to the fourteenth day. The most affected are bagasse and coconut fibres with bagasse been the highest, while the absorption effect on oil palm fibre was minimal.
- SEM results showed that bagasse fibres have rough texture, while coconut and oil palm fibres are smooth in texture. The oil palm fibres looked slightly smoother than

the coconut, and showed a marked tapering diameter as compared to bagasse and coconut fibres.

CHAPTER 6

6 PRE-TEST LABORATORY WORK

6.1 INTRODUCTION

The purpose of conducting the pre-test laboratory work was to investigate the effect of compaction rate for producing soil blocks on the strength properties. This was to find out if low or high compaction rate of manufacturing soil blocks make difference, in order to adopt the appropriate compaction rate for the main field work on fibre reinforced soil blocks. And also to identify some of the issues that need to be improved before the main field work. This work was carried out with only soil without fibres. The chapter therefore describe the preparation and testing of specimens and the results.

6.2 PREPARATION AND TESTING OF SPECIMEN

6.2.1 Preparation of specimen

The main materials used are HI soil sample and water. The soil was weighed and spread on platform. The OMC (11.8%) obtained in Section 4.51 was applies on the soil and mixed until a uniform mixture was obtained (Figure 6.1a). The mixture was used to fill a steel cylindrical mould (in three layers) with a top piston presser which was designed by the researcher. The mould of 40 mm internal diameter and 125 mm length cylinder was filled with soil and compressed to a length of 80 mm with Tinius Olsen H50KS (Figure 6.1b) obtaining as cylindrical specimen of 40 × 80 mm (Figure 6.1c). After the soil was pressed to the required shape and size of the specimen, it was then extruded from the cylinder by using hand pres. The specimens were pressed by the application of four (4) different compaction speed; which were 1 mm/min, 5 mm/min, 10 mm/min and 15 mm/min. The specimens were then placed in an oven for drying at of 40°C (Figure 6.2). After the specimens were dried (when the difference in the successive weights of the cooled sample at interval of 4 hr after 72 hr did not exceed 0.1%), they were set for testing. Three cylindrical specimens were selected for each test type and each compaction speed for the testing.

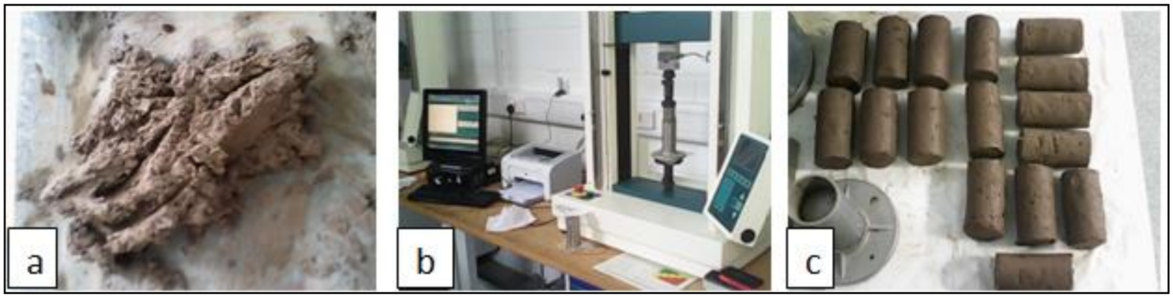


Figure 6.1: Specimen preparation
(a) Wet mixture, (b) specimen under compaction, (c) specimen extruded from mould

Figure 6.2: Drying specimen in oven

6.2.2 Testing of specimen

Four (4) different types of tests were conducted to determine the effect of compaction speed on soil blocks. The tests include density, compressive strength, tensile strength and drip (erosion).

6.2.2.1 Density

Density of the specimen was determined in accordance with British Standard Institute BS EN 772:11 (2011). The specimens were dried at constant temperature of approximately 110°C in an oven for 48 hr until consistent mass was obtained. The dimensions of each specimen were measured and the overall volume computed. The specimens were then weighed and the density of each was calculated form Equation 6.1.

$$\rho = \frac{m}{V} \tag{6.1}$$

Where: ρ is the density (kg/m^3); m is the mass (kg); and V is the volume (m^3).

6.2.2.2 Compressive strength

Compressive strength test was conducted in accordance with British Standard Institute BS EN 772:11 (2011). The test was made with Tinius Olsen H50KS for which three specimens were tested for each rate of pressure application. Each specimen was placed uprightly on the base plate of the testing machine and carefully centred (Figure 6.3a). The load was applied on the specimen until it failed (Figure 6.3b). The maximum load at which the specimen failed was recorded and the compressive strength determined by the Equation 6.2.

$$fc = \frac{\mathrm{F}}{\mathrm{A}} \tag{6.2}$$

Where: f_c is the compressive strength (MPa), F is the applied load at which the block failed (N), A is the surface area of the block where the load was applied (mm^2).

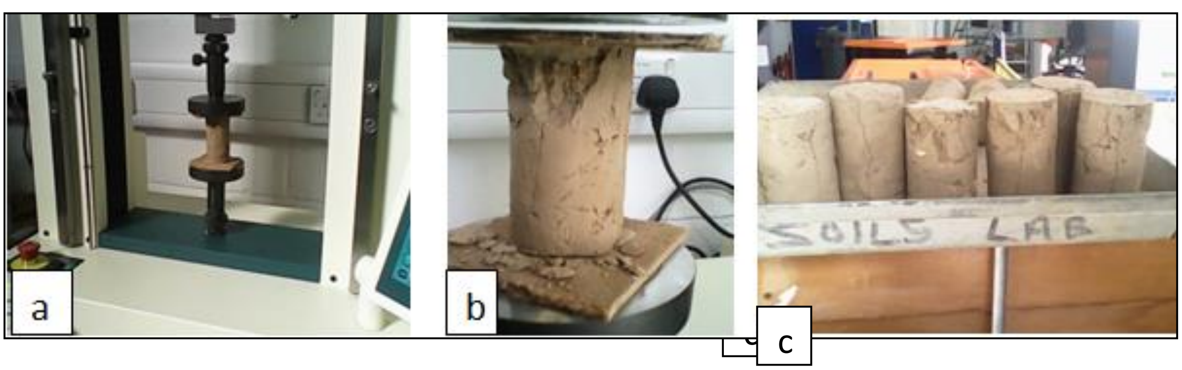


Figure 6.3: Compressive test process

(a) Specimen in test machine, (b) specimen under compressive stress, (c) failed specimen

6.2.2.3 Splitting tensile strength

Splitting tensile strength test was conducted following the principles of British Standard Institute BS EN 12390:6 (2009). Each specimen was placed centrally in the test jig of the Tinius Olsen H50KS, for which the load was applied till the specimen failed (Figure 6.4). The maximum load at which the specimen failed was recorded and the tensile strength determined by the Equation 6.3.

$$ft = \frac{2P}{\pi L d} \tag{6.3}$$

Where: f_t is the indirect tensile strength (MPa); P is the maximum load sustained by the specimen (N); d is the diameter of the specimen (mm) and L is the length of the specimen (mm).

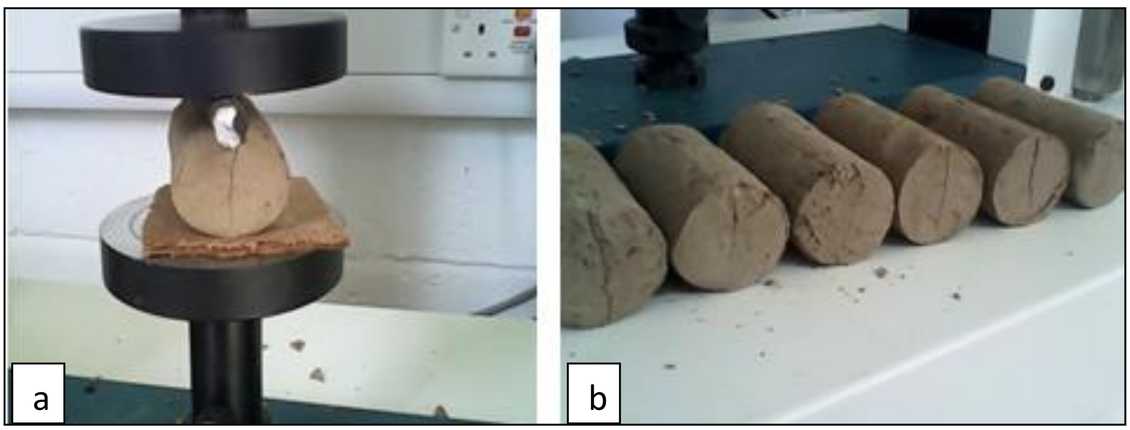


Figure 6.4: Tensile test process
(a) Specimen under tensile stress, (b) failed specimen

6.2.2.4 Drip test (Geelong method)

Drip test was conducted to determine the erodability (durability) of the specimen. Due to the susceptibility of soil blocks, this test aims at determining the rate at which the soil blocks will erode when exposed to water (rain). The test was conducted in accordance with New Zealand Standard (NZS 4298, 1998). The equipment was setup with container containing water for which 100 ml mark from the top was noted. Wettex (J-Cloth) 16 mm wide was placed on the container to soak and transmit the water onto the specimen. The specimen were placed at an angle of 27° at the base and 400 mm vertically away from the J-Cloth, from which water was allowed to drop on the specimen for one hour as shown in Figure 6.5. The depth of the pit (Figure 6.6) created on the specimen was then measured and the erodability index determined.

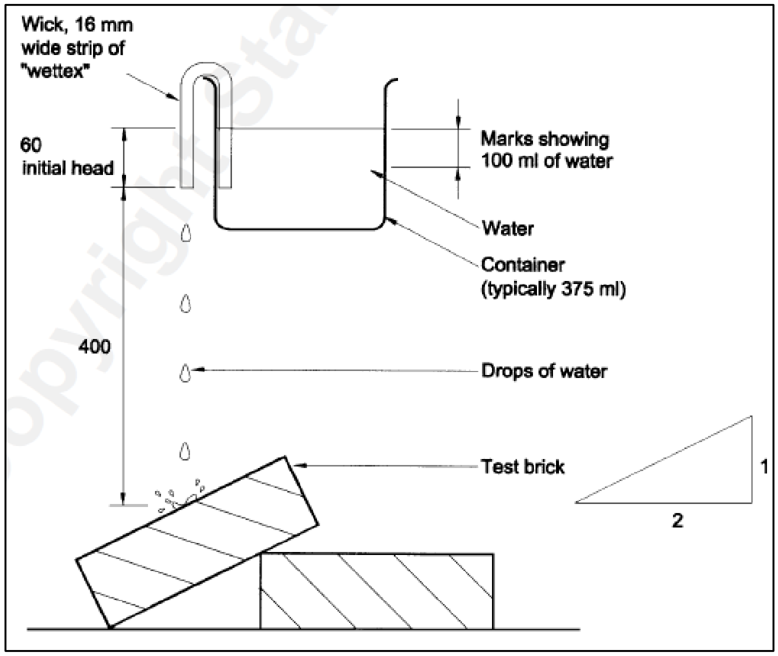


Figure 6.5: Schematic set-up of drip test (NZS 4298, 1998)

Figure 6.6: Drip test specimen showing depth of pit

6.2.3 Statistical analysis

The mean, standard deviation and RSD of the results were determined after normality tests were conducted. Correlations were carried-out to establish relationships between the tests performed. The mean results were used and ranges noted. ANOVA test result at 95% confidence interval with Minitab Version 16 were used to test for significant difference and variation between the test types.

6.3 RESULTS AND DISCUSSION

Details of the result obtained from the pre-test experimental testing are presented in Appendix E.

6.3.1 Dry density

The dry density test results as summarised in Figure 6.7, show a closely related average density among the different compaction rates, between 1866 kg/m^3 and 1894 kg/m^3. Similar results were obtained in the study by Chan (2011), which the non-baked specimens did not undergo obvious density change. This was expected due to the equal mass of the mix used for producing each test specimen. However, there was slight reduction in density from 5 – 15 mm/min compaction rates. The density is the relationship between the volume and the mass of the blocks, and therefore shows how compact the blocks are. The dry density is largely a function of the constituent material characteristics, such as moisture content at pressing and the degree of compaction effort applied (Walker, 1995). This implies that the compaction rates may have some influence on the density of the blocks. Although there was slight difference in the density among the compaction rates, the result indicates that the lower rates (1 and 5 mm/min) of compaction achieved the highest density. This implies that the slower the application of compaction load the better the arrangement of the material constituents, making the block slightly denser. To check if the difference in the test results are significant or not, an ANOVA test was conducted.

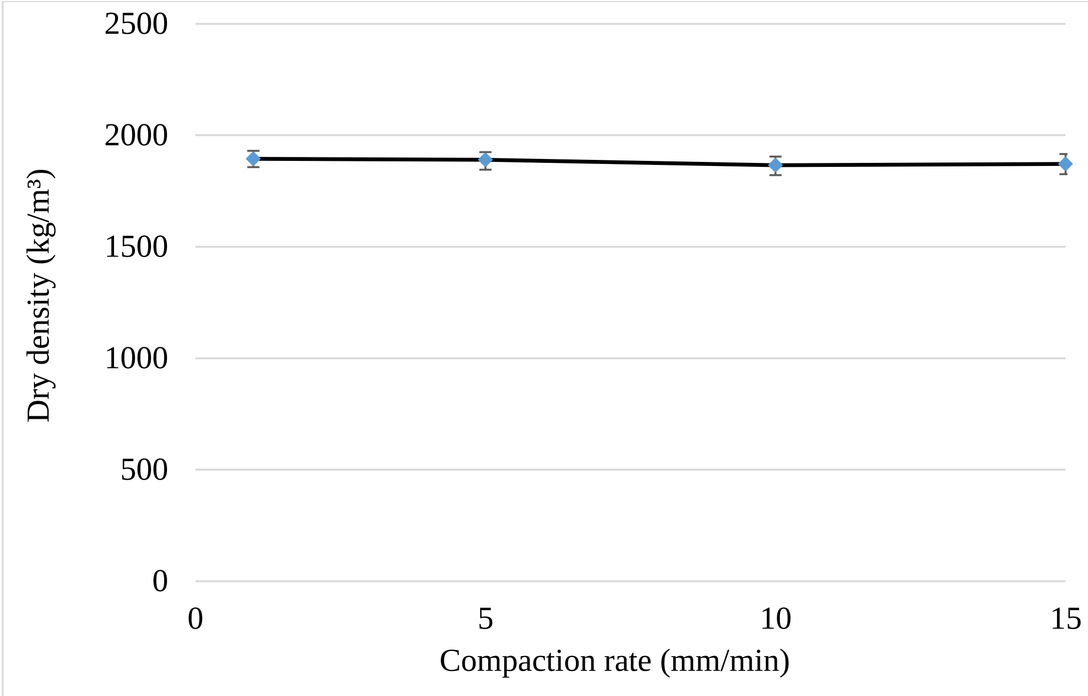


Figure 6.7: Dry density of soil blocks
Error bars represent range of data obtained

ANOVA test results at 95% confidence interval indicates that the differences in the values among the different compaction rates are insignificant to exclude the possibility that the difference is due to random sampling variability. There is therefore not a statistically significant difference (p = 0.799; F = 0.340) in dry density among the compaction rates of the soil blocks.

6.3.2 Compressive strength

Figure 6.8 presents the summary of the compressive strength test results. The results indicate that the average compressive strength decreased with increase in compaction rates. Implying that the higher the compaction rate the lower the compressive strength of the blocks. The reduction could be attributed to the reduce density of the blocks as the compaction rate increases. There was about 19% increase in the average compressive strength of the lower (1 mm/min) compaction rate over the higher (15 mm/min) compaction rate.

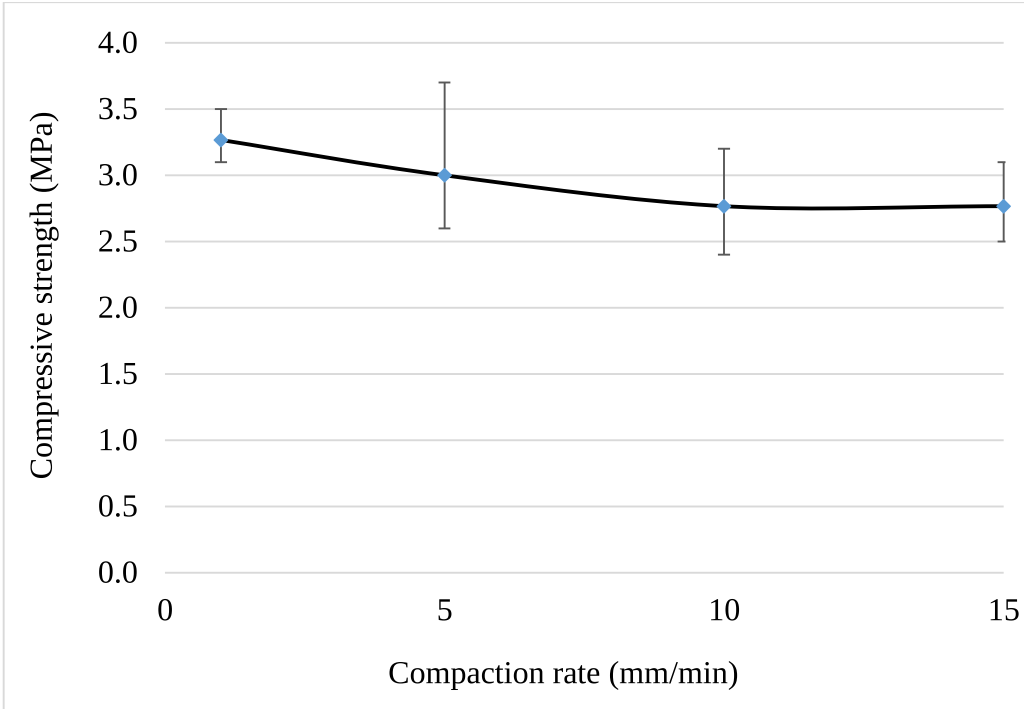


Figure 6.8: Compressive strength of soil blocks
Error bars represent range of data obtained

Figure 6.9 summarises the relationship between the compressive strength and the density of the soil blocks. The results indicate a strong linear relationship between the compressive strength and the density with coefficient of determinant (R^2) of 0.867, though these are based on the means of scattered data. This aligns with Gooding and Thomas (1997) and Walker (1995) observation that a given increase in density will result in a greater increase in strength.

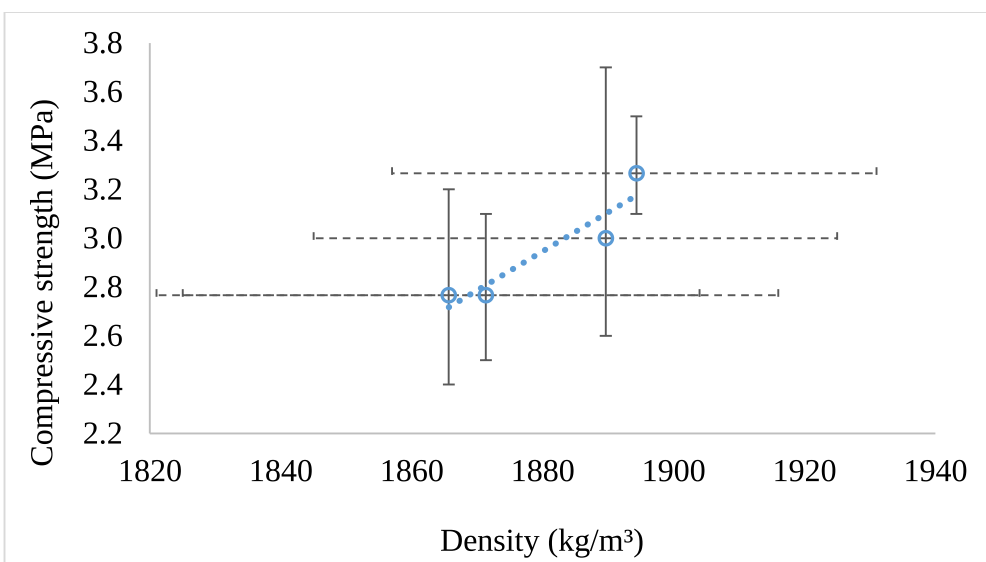


Figure 6.9: Relationship between compressive strength and density of soil blocks

Error bars represent range of data obtained

ANOVA test result indicates that the differences in the values among the different compaction rates are insignificant to exclude the possibility that the difference is due to random sampling variability. There is therefore not a statistically significant difference (p = 0.410; F = 1.010) in compressive strength among the compaction rates of the soil blocks.

6.3.3 Splitting tensile strength

The summary of the splitting tensile strength test result is presented in Figure 6.10. The result is similar to the compressive strength, however, the 10 mm/min speed recorded an increase in tensile strength than both 5 and 15 mm/min compaction rates. The lower compaction rate recorded the highest strength while the highest compaction recorded the lowest as in the case of compressive strength. This suggests that the lower compaction rate application makes the soil particles arrange to eliminate bigger pores in the soil matrix, which contributes to the increase resistance of the material against splitting failure.

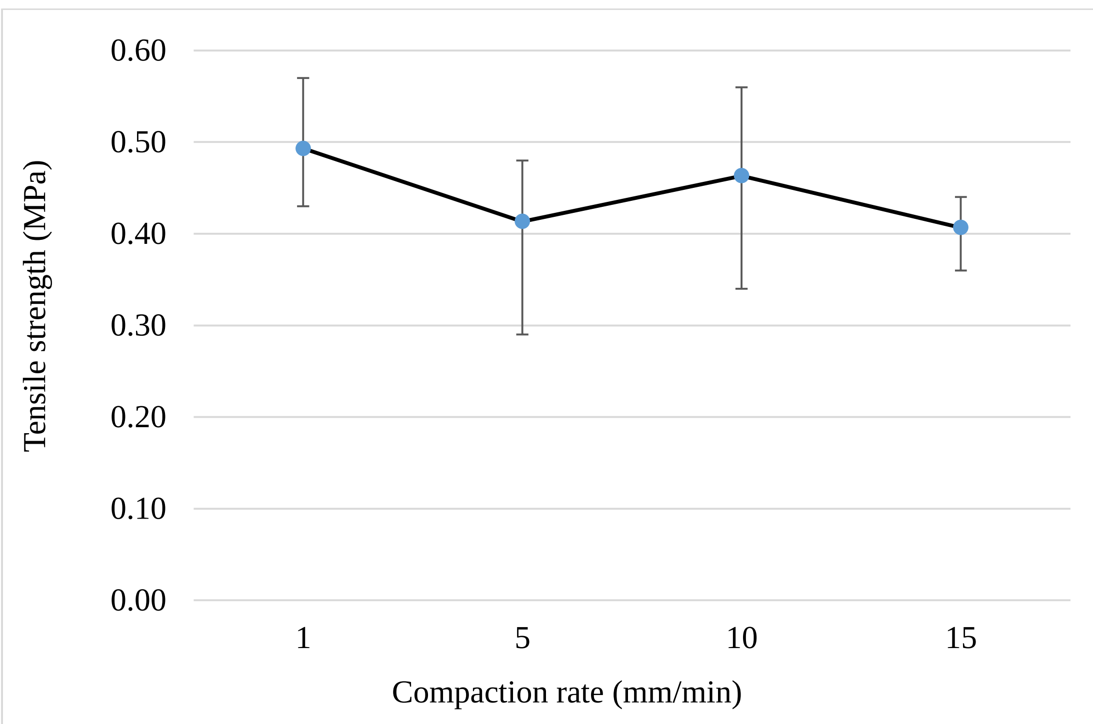


Figure 6.10: Tensile strength of soil blocks
Error bars represent range of data obtained

There was about 20% average tensile strength increase of the lower compaction rate over the higher compaction rate, which was similar to the compressive strength results. The ANOVA test result indicates that there is not a statistical significant difference (p = 0.596; F = 0.670) between the compaction rates of the soil blocks.

The relationship between tensile strength and compressive strength, and tensile strength and density of the soil blocks can be found in Figures 6.11 and 6.12 respectively. The results indicate a weak linear relationship between tensile strength and compressive strength, and tensile strength and density with coefficient of determinant (R^2) of 0.346 and 0.070, respectively, though these are based on the means of scattered data.

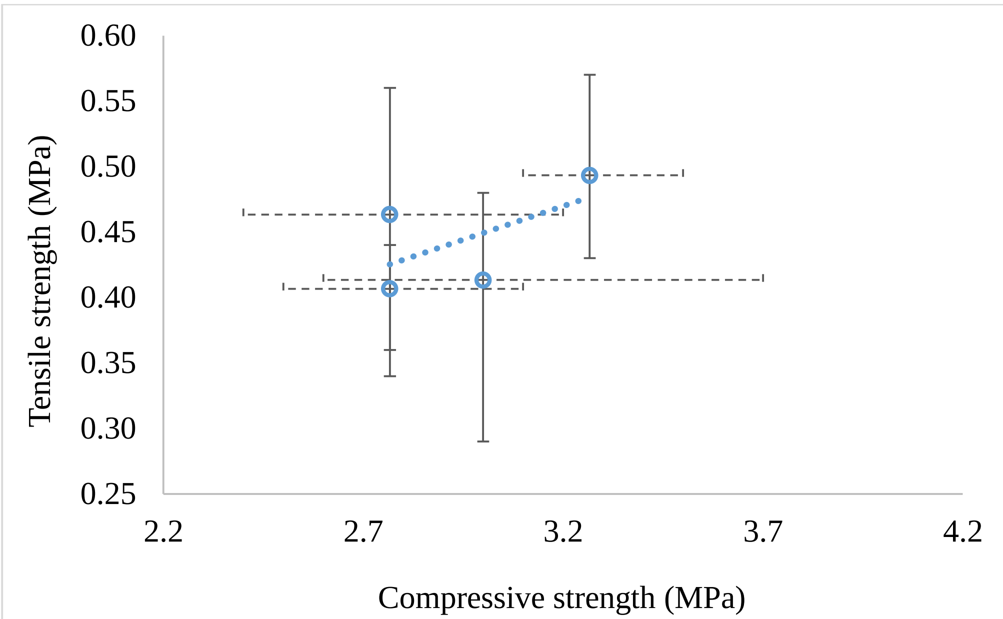


Figure 6.11: Relationship between tensile and compressive strengths of blocks
Error bars represent range of data obtained

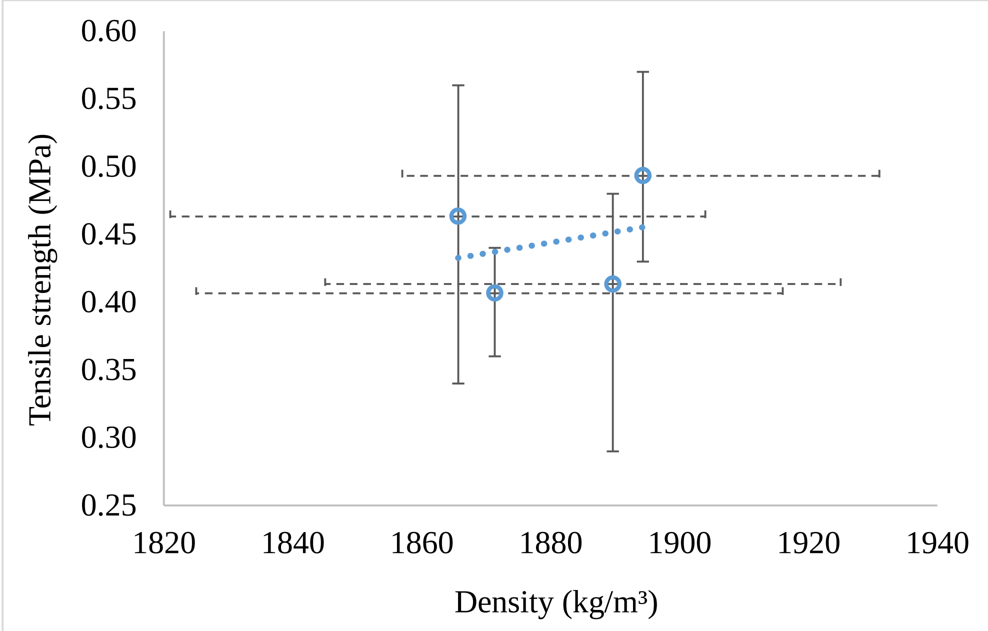


Figure 6.12: Relationship between tensile strength and density of soil blocks
Error bars represent range of data obtained

6.3.4 Erosion test

A summary of the drip test results is provided in Table 6.1. It can clearly be seen from the results that the depth of pit increased with the increase in compaction rates. This shows some similarities in the results of the density test, where density of the blocks reduced with increased compaction rates. This suggests that densification of the blocks may affects the rate of the erosion of the soil blocks. The low rate of compaction increased slightly the density of the soil blocks and therefore may have reduced the erodability rate. This means that the lower the compaction rate of producing soil blocks, the lower the effect of erosion by rain or water on the blocks.

Table 6.1: Drip test results

Compaction rate (mm/min)	Average depth of pit (mm)	Erodability index (E_I)	Rating
1	6.2	3	Erosive
5	7.0	3	Erosive
10	7.3	3	Erosive
15	8.2	3	Erosive

E_I 1=0 (Non-erosive), E_I 2=0<5 (Slightly erosive), E_I 3=>5≤10 (Erosive), E_I 4=>10 (Very erosive)

The results show that the depth of pit for all the compaction rates were within erodabilty index of 3, which means they were all erosive (NZS 4298, 1998). However, the low compaction rate performance was better than the higher rates. Conversely, the test of significant difference (Table 6.1) indicates that there is not a statistically significant difference (p = 0.458; F = 1.26) among the compaction rates during block production.

Figures 6.13 and 6.14 show the relationship between erosion and density, and erosion and tensile strength respectively of the soil blocks. The results indicate good linear relationship between tensile strength and density, and tensile strength and compressive strength with coefficient of determinant (R^2) of 0.612 and 0.831, respectively, though these are based on the means of scattered data.

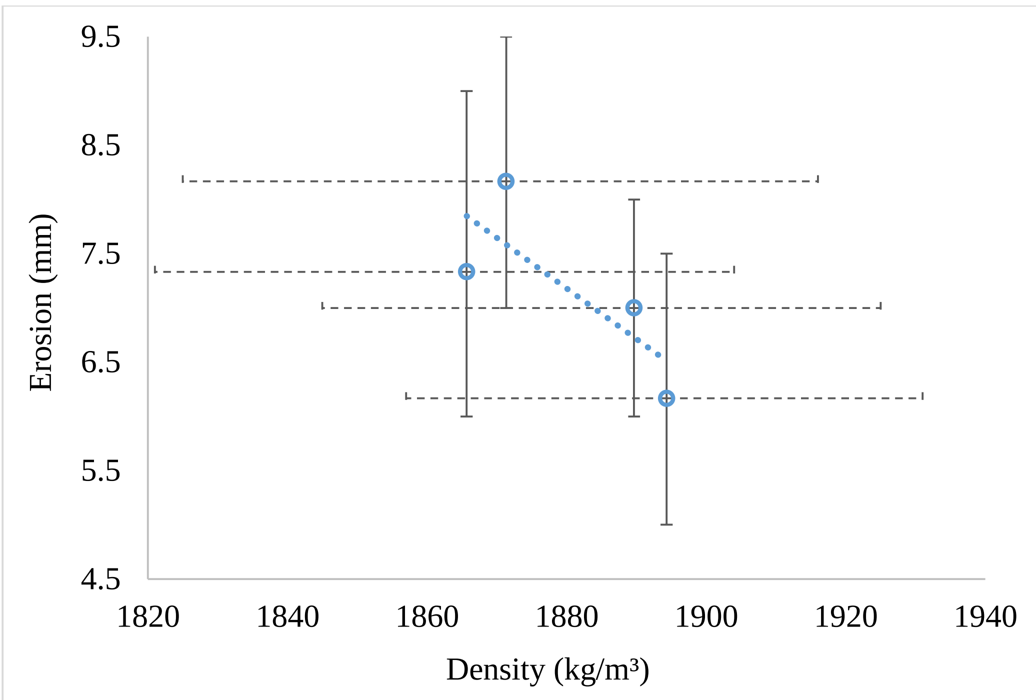


Figure 6.13: Relationship between erosion and density of soil blocks
Error bars represent range of data obtained

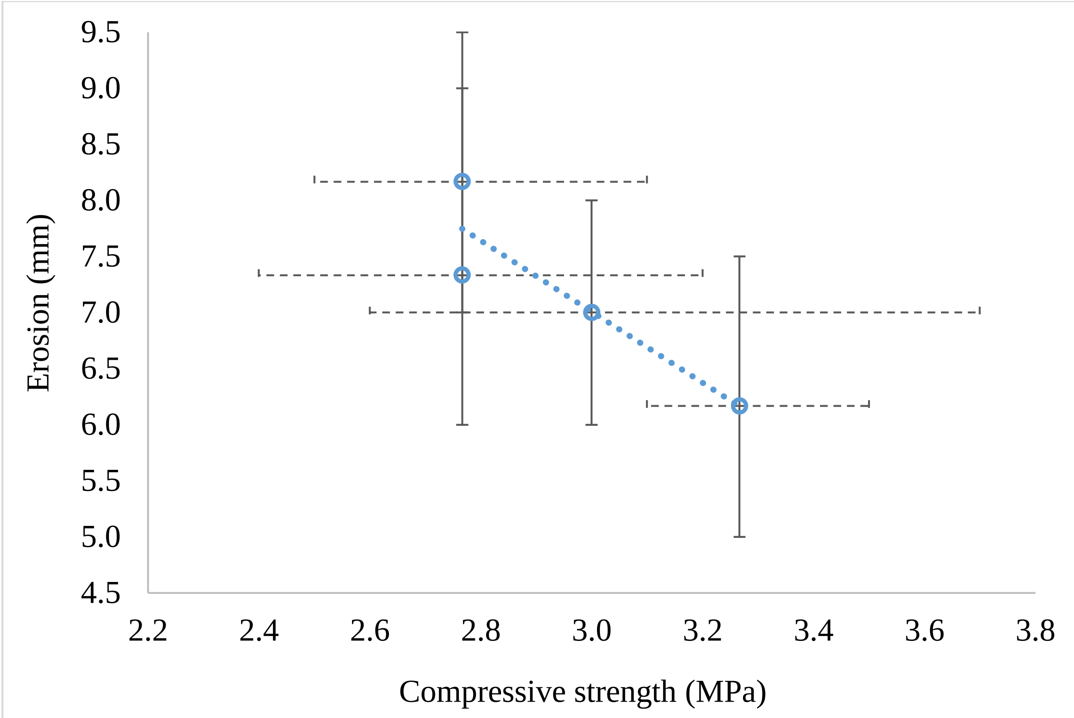


Figure 6.14: Relationship between erosion and compressive strength of soil blocks
Error bars represent range of data obtained

6.4 OBSERVATIONS MADE

The following observations were made during the pre-test experimental work:

- The mixing was difficult due to the clay content in the soil which made the mixture sticky and difficult to turn as compared to mixing cement-sand mortar. It is therefore important to avoid large mixes in the main field work, particularly when fibres will be added to ensure uniform mix.
- There was difficulty in extruding the freshly made specimen from the cylindrical mould. Handling of the fresh specimen left some finger prints on them. There is the need to leave the specimen in the mould over-night for the specimen to set before extruding to prevent such problems from occurring. If possible, the use of cylindrical mould should be avoided in the main field work.
- In most cases, the joints between the three layers of the specimen were visible. This means there is the possibility of lack of bond between them, which may affect the

blocks strength. The use of a mixture to fill the mould instead multiple layers of filling will be appropriate in the field work.

- Lack of specified compaction pressure in making the blocks could also affect the properties. It is therefore essential to adopt common compaction pressure in making the field experimental work.
- The Geelong test for erosion was found to require a well set-up equipment in the laboratory setting, and therefore might not be very appropriate for field work testing of blocks. Therefore, the use of water spray erosion test could be adopted for the main field work on fibre reinforced soil blocks.

6.5 SUMMARY

The aim of this chapter was to investigate the effect of compaction rates for producing soil blocks on the engineering properties of the blocks. This laboratory work was a preparatory work that was conducted before the main experimental works were carried out in the Chapters 7 to 9. It consisted mainly of preparation and testing of specimen, results and discussion and observations made during the pre-test laboratory works. The tests conducted include dry density, compressive strength, splitting tensile strength and erosion (drip). A number of issues were encountered during the investigation that need attention before the main experimental works were started. The main conclusion of the investigation can be found in Section 12.2. The following concluding remarks can be made:

- Test of significance by ANOVA at 95% confidence interval for all the test types proved that there was not a statistically significant difference among the different compaction rates of producing the soil blocks. However, the lower compaction rate for producing soil blocks obtained a slightly better performance characteristics in terms of physical, mechanical and durability.

- There was a relationship between the test types. Thus, the compressive strength test result could be associated with the density test result of the blocks. There was also a similar trend in the test results of compressive strength and the tensile strength. Similarly, there was a common trend in the test results of the density and the erosion.

CHAPTER 7

7 FIBRE ASPECT RATIO

7.1 INTRODUCTION

This chapter investigates the effect of aspect ratio of coconut, bagasse and oil palm fibres on the mechanical properties of soil blocks. This was done in order to determine the fibre lengths that will produce optimum strength of the enhanced soil blocks. This is necessary to determine the cut lengths of the fibre types to be used in properties of natural fibre reinforced soil blocks study in the next chapter (Chapter 8).

7.2 MATERIALS AND METHODS

7.2.1 Materials

The main materials used for the investigation are (1) soil, (2) agricultural waste fibres and (3) water. Soil B as described in Section 4.2 was used. Summary of the properties of the soil can be found in Section 4.6.

Coconut, bagasse and oil palm fibres were used for the investigation, and details of the fibres are available in Chapter 5. To obtain the required fibre sizes, nominal diameters were determined by taking the mean of 100 measurements for each fibre type and the fibre lengths were obtained by multiplying the nominal diameter by the required aspect ratio. The results obtained are shown in Table 7.1. The fibres were cut to the aspect ratio lengths (25, 50, 75, 100 and 125) which were limited by the fibre lengths available. It should be noted that, as there are a range of diameters of fibre present in each block, the corresponding aspect ratio will also vary with the same relative standard deviation as quoted for diameter.

Tap water was used because of its clean nature which is relatively free from any impurity that might have any effect on the properties of the blocks. Water from the tap of the Blocks Production Unit of Sunyani Polytechnic, Ghana was used.

Table 7.1: Required length of fibre for aspect ratios

Fibre Type	Mean Diameter (mm)	Std Dev (mm)	RSD (%)	Anderson-Darling Normality (p-value)	Aspect Ratio				
					25	50	75	100	125
Coconut	0.40	0.17	42.5	0.065	-	20 mm	30 mm	40 mm	50 mm
Bagasse	0.78	0.19	23.8	0.270	-	40 mm	60 mm	80 mm	100 mm
Oil Palm	0.38	0.08	23.7	0.075	10 mm	19 mm	28 mm	38 mm	-

7.2.2 Block making machine

A pressure gauge block making machine was obtained following BREPAK machine mechanism. The machine was fitted with a hydraulic system and meter gauge which helped in applying constant pressure for making the blocks. Details of the parts of the machine can be seen in Figure 7.1.

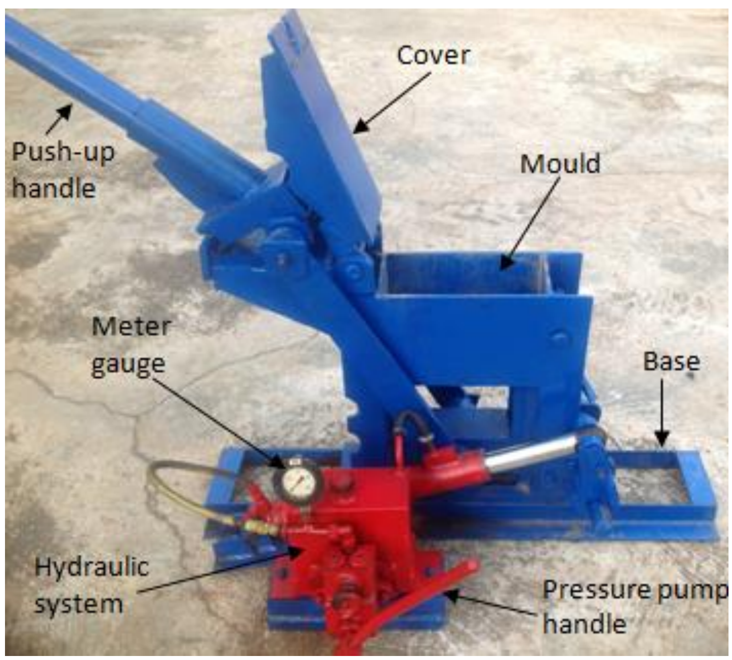


Figure 7.1: Pressure gauge block making machine

7.2.3 Preparation of fibre-enhanced soil blocks

The processes involved in preparing the samples for testing are presented in Figure 7.2. The figure shows the procedure followed in making the enhanced soil blocks with agricultural waste fibres. Enhanced soil blocks of 290 × 140 × 100 mm were made. This size was derived from the recommendations and what previous studies used (Table 7.2). According to New Zealand Standard NZS 4298 (1998), there is no preferred size for earth blocks; however, the minimum length should be 280 mm, it makes recommendation of 290-300 mm length × 140±2 mm width × 90-102 mm thickness.

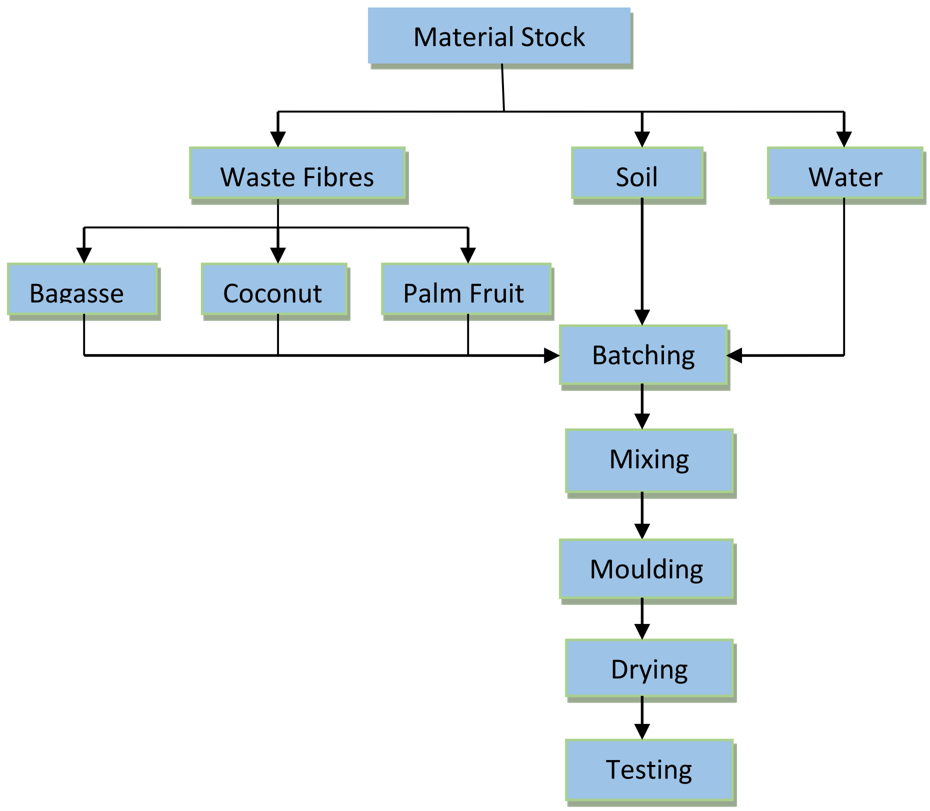


Figure 7.2: Process involved in preparing test samples

Table 7.2: Recommended block sizes

Reference	**Block size (mm)**
NZS 4298 (1998)	290-300 × 140±2 × 90-102
Alavéz-Ramírez et al. (2012)	300 × 150 × 120
Bouhicha et al. (2005)	220 × 107 × 60
	60 × 60 × 36
Millogo et al. (2014)	295 × 140 × 100

One percent (1%) fibre by weight was used as this was the maximum fibre content recommended by previous studies (Millogo et al., 2014, Obonyo et al., 2010b, Yalley, 2012).

The soil was first spread on a platform, then the fibre was spread on top and turned over and over until a uniform mixture was obtained. Water was added to achieve the optimum moisture content (see Section 4.5.1) by sprinkling on the soil-fibre mixture and repeatedly turned to obtain a homogenous mixture (Figure 7.3). The mix was weighed (8.6 kg for each block), filled the mould, hydraulically compressed at 100 bar (10 MPa) pressure and then pushed up (Figure 7.4). The blocks were sun dried at an average temperature of 27°C and relative humidity of 72% for 21 days (Figure 7.5) before testing.

Figure 7.3: Wet mixture of soil and fibre

Figure 7.4: Process involved in demoulding test samples

Figure 7.5: Drying of soil blocks

7.2.4 Testing of blocks

Compressive and tensile splitting tests were conducted to determine the mechanical properties of the blocks. Five blocks for each aspect ratio mix and fibre type were selected for each test. In all 120 blocks were tested as shown in Table 7.3.

Table 7.3: Quantity of blocks tested

Test	**Fibre Aspect Ratio**					
	25	**50**	**75**	**100**	**125**	***Total***
Compressive	5	15	15	15	10	***60***
Tensile	5	15	15	15	10	***60***
Total	***10***	***30***	***30***	***30***	***20***	***120***

15 replicates represent 5 samples for each of the three fibre types; 10 replicates represent 5 samples for two fibre types; and 5 replicates represent 5 samples for a fibre type based on the availability of the fibre length as shown in Table 7.1.

7.2.4.1 Compressive Strength test

The purpose of conducting the compressive strength test is to find out the ability of the blocks to resist applied load in compression. The test was conducted in accordance with British Standard Institute BS EN 772:1 (2011). Testing machine (CONTROLS 50-C46G2) with maximum capacity 2000 kN was used for conducting the test. The load was applied at a rate of 0.05 $N/mm^2/s$ until the block failed, the load at which the blocks failed (Figure 7.6) was recorded and maximum compressive stress was calculated by the Equation 6.2 in Section 6.2.2.2.

Figure 7.6: Compressive test set-up with failed block

7.2.4.2 Splitting tensile strength test

The purpose of this test is to measure the resistance of the block when a load is applied at the central point which tends to split the block into two. Tensile strength has direct bearing on determining the suitability of most pressed earth block applications, just like compressive strength. It can be a useful indicator for measuring the overall strength properties of blocks. Tensile strength test was conducted in accordance with British Standard Institute BS EN 1338 (2003). Testing machine CONTROLS 50-C46G2 with splitting component attached was used for conducting the test.

Each block was placed in the testing machine without using any extra packing. The splitting jig components were placed centrally above and below the block. The testing machine was started and applied load at a rate of 0.05 $N/mm^2/s$ until the block failed (Figure 7.7). The maximum load at which the blocks failed was recorded. The tensile splitting strength of the blocks was then calculated from the Equation 7.1.

$$T = 0.637 \times k \times \frac{\mathrm{P}}{\mathrm{S}} \tag{7.1}$$

Where: *T* is the tensile strength (MPa), 0.637 is constant, *k* is correction coefficient of block thickness (Table 7.4), *P* is the failure load (N), *S* is the cross sectional area of the block where the load was applied (mm^2).

Figure 7.7: Tensile test set-up

Table 7.4: Recommended correction coefficient (k) for block thickness
(British Standard Institute BS EN 1338, 2003)

***t* (mm)**	40	50	60	70	80	90	100	110	120	130	140
k	0.71	0.79	0.87	0.94	1.00	1.06	1.11	1.15	1.19	1.23	1.25

7.3 RESULTS AND DISCUSSION

The results obtained are presented as follows: (1) effect of fibre aspect ratio on compressive strength, (2) effect of fibre aspect ratio on tensile strength and (3) relationship between compressive and tensile strengths effect on fibre aspect ratio. Further details of the test results are reported in Appendix F.

7.3.1 Effect of fibre aspect ratio on compressive strength

Figure 7.8 summarises the compressive strength tests results for the fibre aspect ratios tested. More details can be found in Appendix F. It can be seen that for coconut fibre, the increase of fibre aspect ratio up to 125 increased the compressive strength by about 26% compared to the aspect ratio of 50. Oil palm fibres show a continual increase up to 100 which is the maximum possible for this fibre, resulting in an increase of 14% over a ratio of 50 and 19% over a an aspect ratio of 25, the smallest aspect ratio tested. Bagasse fibres displayed an optimum aspect ratio of 100 with a 32% improvement on the initial aspect ratio of 50.

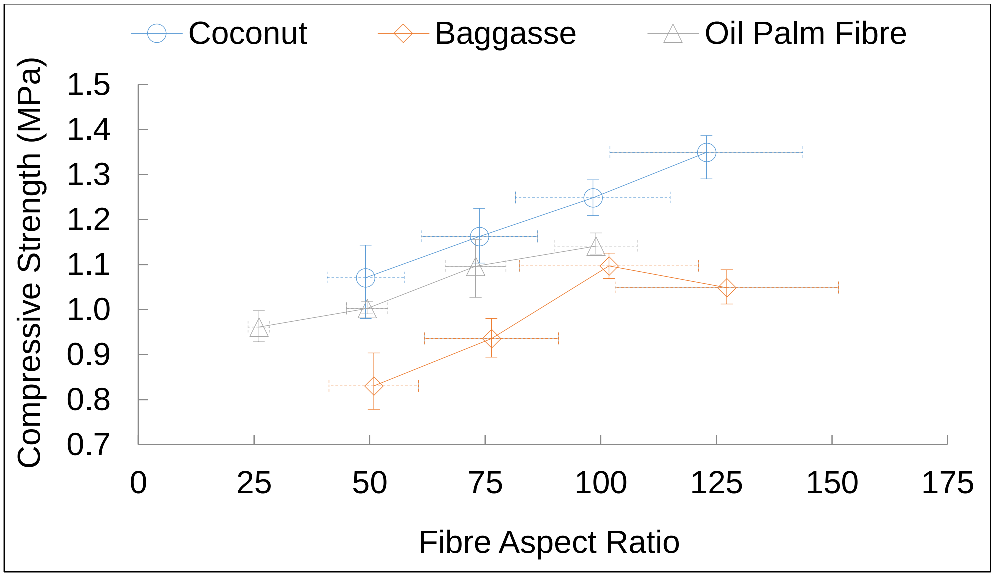


Figure 7.8: Compressive strength variation with fibre aspect ratio
Vertical error bars represent the range of values found. Dotted horizontal error bars represent 1 standard deviation in fibre aspect ratio found in the block due to variations in fibre diameter.

The result of coconut fibre is similar to the result of a study conducted by Yalley (2012), which coconut fibre enhanced concrete obtained the highest compressive strength with a fibre aspect ratio of 125. It must however be noted that the actual theoretical maxima may be higher still, but is constrained by the fibre lengths available. For bagasse fibre, there was a 5% (for fibre aspect ratio125) decrease after the optimum compressive strength was achieved at a fibre aspect ratio of 100. Furthermore, not all fibre types will produce continually increasing compressive strength with increase of fibre length, making the determination of the optimum aspect ratio an important step in the specification of enhanced soil blocks.

It is likely that the increase in strength caused by longer fibres is due to greater adhesion of the fibre to the matrix caused either by greater friction and/or cohesion between the fibre and the matrix or looping of the fibre in the matrix. Longer fibres will also be more effective as the block matrix fails, as longer fibres will form longer bridges across cracks and are less likely to be anchored in a part of the matrix that has separated from the rest of the block.

Previous studies concentrating on fibre quantity have commented that reductions in performance occur when fibres begin to knot together (Ismail and Yaacob, 2011) resulting in lost cohesion with the soil (Medjo Eko et al., 2012) or break-up of the soil matrix (Millogo et al., 2014) causing the soil-fibre composite to weaken. It is likely that these factors also cause blocks with very long flexible fibres to reduce in strength. Other potential causes are that very long fibres may fail to disperse or distribute evenly within the matrix (Millogo et al., 2014) or form a multifilament structure (Bentur and Akers, 1989) in soil during mixing and therefore increase the local porosity of the reinforced soil blocks.

7.3.2 Effect of fibre aspect ratio on tensile strength

Appendix F gives the details of the tensile strength tests as well as compressive strength results while Figure 7.9 summarises the tensile strength results. The trend of the results is similar to that of the compressive strength. Coconut fibres have a rising strength until the longest samples available with an aspect ratio of 125. Similarly, oil palm rises until its maximum aspect ratio of 100 and bagasse displays an optimum of an aspect ratio of 100. The increase in tensile strength was up to 61%, 24% and 20% respectively for coconut, bagasse and oil palm fibres. Failure of the fibre enhanced soil blocks was with multiple finer cracks with a gradual failure resembling a ductile material which agrees well with Cai et al. (2006).

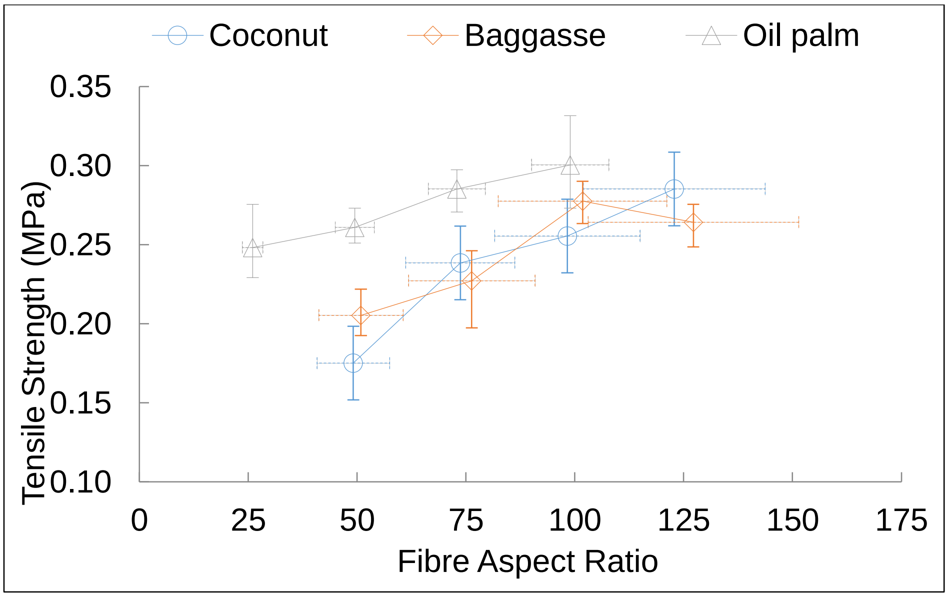


Figure 7.9: Tensile splitting strength variation with fibre aspect ratio
Vertical error bars represent the range of values found. Dotted horizontal error bars represent 1 standard deviation in fibre aspect ratio found in the block due to variations in fibre diameter.

Upon removal from the testing machine, it became apparent that although the blocks were split into two, the two parts were still held together by the fibres (Figure 7.10). This indicates that blocks will fail slowly rather than suddenly and will still hold a load (albeit with considerable deformation) sometime after failure.

Figure 7.10: Split block held together by fibres

7.3.3 Relationship between compressive and tensile strengths

Inspection of the compressive and tensile results shows that in both results bagasse fibre recorded an optimum strength at fibre aspect ratio 100 while coconut and oil palm fibres obtained peak strength at fibre aspect ratios 125 and 100 respectively. The relation between compressive strength and tensile strength was achieved using scatter plot with trend lines and error bars. Figure 7.11 summarises the results which indicate a strong linear relationship between compressive and tensile strengths of the enhanced soil blocks with coefficients of determination (R^2) of 0.939, 0.978 and 0.998 for coconut, bagasse and oil palm fibres respectively, though these are based on the means of a range of data.

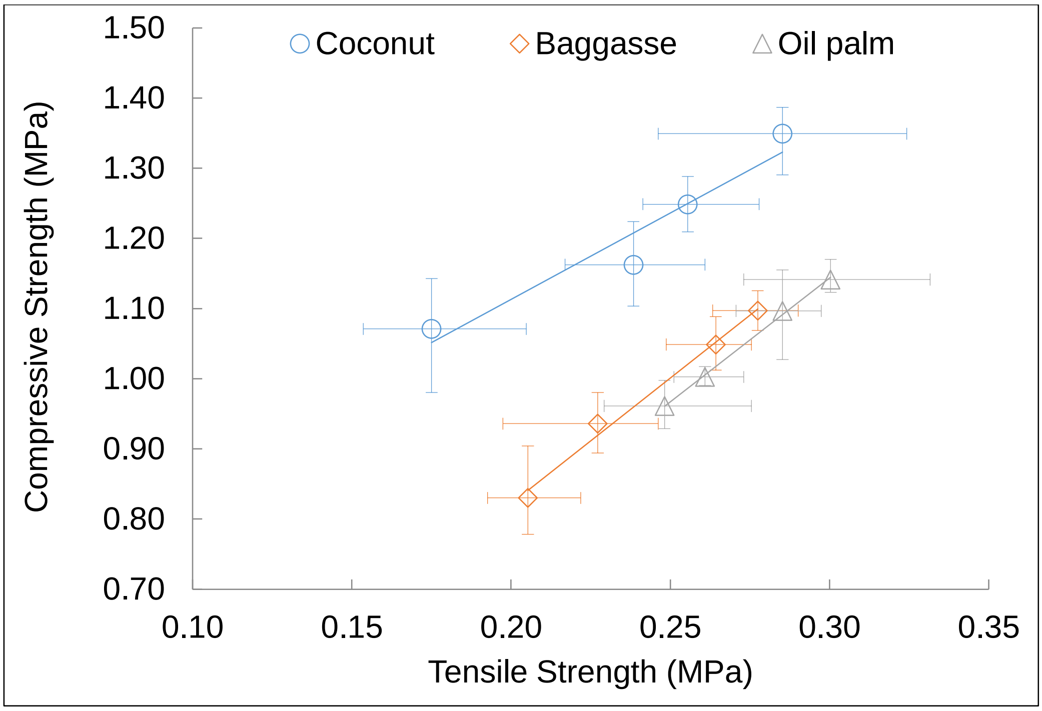


Figure 7.11: Relationship between compressive and tensile strengths
Error bars represent the range of values obtained

The relationship of compressive and tensile strength is given by a gradient of 2.46, 3.58 and 3.53 for coconut, bagasse and oil palm fibres respectively. This agrees fairly well with a previous study which found compression to flexural/tensile ratios in the order of 4 (Danso et al., 2015a).

7.4 SUMMARY

In this part of the study, the effect of aspect ratio of three different agricultural waste fibres on the mechanical properties of soil blocks was investigated. The tests conducted are compressive strength and splitting tensile strength. The results obtained were discussed under effect of fibre aspect ratio on compressive strength, effect of fibre aspect ratio on tensile strength and relationship between compressive and tensile strength effect on fibre aspect ratio. Optimum fibre lengths of 50, 80 and 38 mm for coconut, bagasse and oil palm fibres, respectively, were found to be more suitable for used in the study to determine the properties of natural fibre reinforced soil blocks in the next chapter (Chapter 8). The main conclusion of the investigation can be found in Section 12.2. The following summary remarks can be made:

- The coconut fibre aspect ratio that could produce the maximum compressive and tensile strengths of soil blocks may be 125 or higher. In terms of linear dimension, it translates into length of 50 mm or higher of the coconut fibre. This produced about 25% improvement in compressive strength and more than half in tensile strength over the smallest fibre aspect ratio tested.
- Bagasse fibre achieved an optimum compressive and tensile strengths at an aspect ratio of 100, which in terms of length of the fibre is 80 mm. This produced about 25% improvement over the smallest fibre aspect ratio for both compressive and tensile strengths.
- The highest available aspect ratio of 100 for oil palm fibre recorded the highest value for both compressive and tensile strengths. This aspect ratio was equivalent in length to 38 mm. There was about 20% improvement in peak compressive and tensile strengths over the smallest aspect ratio.
- There was a strong linear relationship between compressive and tensile strengths of the enhanced soil blocks for each of the fibre aspect ratio for each fibre type.

CHAPTER 8

8 PHYSICAL, MECHANICAL AND DURABILITY PROPERTIES OF SOIL BLOCKS REINFORCED WITH DIFFERENT FIBRE CONTENTS

8.1 INTRODUCTION

This chapter investigates the properties of soil building blocks reinforced with the three fibres (see Section 5.3) in two different soils (R and B, see Section 4.2). To achieve this, the physical, mechanical and durability properties of the fibre reinforced soil blocks were measured and optimum fibre content determined. The applicability of proxy measures, such as physical properties for strength and durability, were then evaluated as these have been shown to be applicable to blocks reinforced with binders, such as Portland cement (Venkatarama Reddy and Jagadish, 1995, Walker, 2004), but not well defined for blocks reinforced with fibres. The relative importance of soil-type and fibre type in determining the properties of fibre reinforced earth blocks were then assessed. These were then compared to the published criteria for soil suitability which have been generally developed for binder stabilised blocks (Houben and Guillaud, 1994) and therefore may not be appropriate for fibres. This work extends the existing database of different fibres used for reinforcement of soils blocks across a range of performance measures and evaluates them against the existing guidance.

8.2 MATERIALS AND METHODS

8.2.1 Materials

Soil, agricultural waste fibres and water were the main materials used for this investigation. Soils B and R as described in Section 4.2 were used. Summary of the properties of the soils can be found in Section 4.6. The three fibres described in Section 5.2 were used and their properties can be found in Chapter 5. The water described in Section 7.2.1 was used.

8.2.2 Preparation of fibre enhanced soil blocks

Details of the block making machine used are described in Section 7.2.2. The preparation of the fibre enhanced soil blocks followed the same process in Section 7.2.3. The only difference is that 0.25, 0.5, 0.75 and 1% fibre content by weight were used instead of only 1%. And the aspect ratios were kept to 50, 80 and 38 mm optimum lengths for coconut, bagasse and oil palm fibres, respectively, as were found in Chapter 7. These fibre contents were derived from previous studies (Table 8.1).

Table 8.1: Fibre contents from previous studies

Reference	**Fibre contents (wt %)**
Millogo et al. (2014)	0.2, 0.4, 0.6, 0.8
Juárez et al. (2010)	0.25, 0.5, 0.75, 1
Yalley and Kwan (2008)	0.75, 1.0, 1.5
Chan (2011)	0.25, 0.5, 0.75

These studies used different fibre content by weight, from which this current study adopt 0.25%, 0.5%, 0.75% and 1.0% fibre content by weight. The adopted range of the mix ratios of the studies helped to provide more test samples that determined the ratio that achieved the optimum and peak results. Previous trials showed that fibre percentage more than 1% does not appear to be good due to the poor texture and appearance after drying of the blocks (Figure 8.1). At this point, the edges of the blocks break easily and the block appears not to be strong enough. Figure 8.2 shows the drying of some of the fibre enhanced soil blocks.

Figure 8.1: Appearance of soil blocks enhanced with 1.25 and 1.5% fibre content

Figure 8.2: Drying of enhanced soil blocks
(R) Indicate red soil blocks, (B) indicate brown soil blocks

8.2.3 Testing of blocks

Seven different tests were carried out on the fibre enhanced soil blocks. These included density, linear shrinkage, water absorption, compressive strength, tensile splitting, wearing and erosion. These tests were selected to cover a wide range of properties important for soil blocks, such as physical, mechanical and durability after a review of previous studies in Section 3.2.4. The details of the samples tested can be found in Table 8.2. Figure 8.3 shows some samples of the blocks that are ready for testing.

Figure 8.3: Fibre enhanced soil blocks ready for testing
(R) Indicate red soil blocks, (B) indicate brow soil blocks

Table 8.2: Quantity of blocks prepared

Test		Fibre (%)					Fibres	Soil
		0	0.25	0.5	0.75	1	(×3)	(×2)
Physical	Density and linear shrinkage	5	5	5	5	5	75	150
	Water absorption	5	5	5	5	5	75	150
Mechanical	Compressive	5	5	5	5	5	75	150
	Tensile	5	5	5	5	5	75	150
Durability	Wearing (Wire brush)	5	5	5	5	5	75	150
	Erosion (Spray)	5	5	5	5	5	75	150
Total		***30***	***30***	***30***	***30***	***30***	***450***	***900***

8.2.3.1 Physical properties

Three tests were conducted to determine the physical properties of the enhanced soil blocks; these are density, water absorption by capillary and linear shrinkage tests.

Density test

Density of the specimen was determined in accordance with British Standard Institute BS EN 771:1 (2003). The blocks were gently wiped with cloth in order to remove any dust or loose matter stuck to them. Each dimension of these blocks (Figure 8.4) along the edge was measured and the average calculated. The density was then determined following the process in Section 6.2.2.1 with Equation 6.1.

$$Length = \frac{L1+L2+L3+L4}{4} \quad (8.1)$$

$$Thickness = \frac{T1+T2+T3+T4}{4} \quad (8.2)$$

$$Width = \frac{W1+W2+W3+W4}{4} \quad (8.3)$$

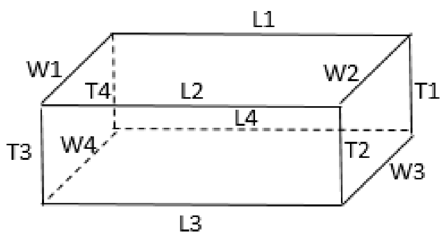


Figure 8.4: Block dimensions

Linear shrinkage test

Linear shrinkage (LS) test was performed to determine the fibre enhanced soil blocks ability to resist deformation of all dimensions of the blocks which is caused by drying or the evaporation of water. Shrinkage control is important to reduce deformation and cracking of the blocks. The test was performed following the process of British Standard Institute BS EN 772:14 (2002). The linear shrinkage (change in length) was measured using a dial gauge. The lengths of the fresh (green) blocks were measured (WL). The blocks were then allowed to dry and the lengths measured again (DL). The lengths were determined and the percentage reduction in length was calculated in the Equation 8.4.

$$LS = \frac{WL - DL}{WL} \times 100 \tag{8.4}$$

Water absorption by capillarity test

The water absorption test was conducted to measure the ability of the enhanced soil blocks to resist the absorption and retention of water. One of the characteristics of soil blocks is their ability to absorb and retain water. The aim of conducting this test was to determine the rate at which the enhanced soil blocks absorb and retain water through capillary action, in order to take the necessary steps to reduce the effect. The capillary test was used to prevent the blocks from dissolving when fully immerse in water. The test was performed in accordance with British Standard Institute BS EN 772:11 (2011) procedure for clay masonry units. The main apparatus used for this test are weighing balance and container. The mass of the specimens were taken and recorded (m_1). The 290 × 140 mm side of the specimen was immersed to a depth of 5 mm in a constant head-water bath for 10 min (Figure 8.5). The mass of the absorbed specimen was recorded and the absorption of water by capillarity rise was then calculated in the equation 8.5. W_A

$$Cw,s = \left(\frac{Mt - Mi}{A\sqrt{t}}\right) \tag{8.5}$$

Where $C_{W,S}$ is coefficient of water absorption by capillary (kg/(m^2 × min), M_t is mass of the specimen after t (kg), M_i is the initial mass of specimen (kg), A is area of block in contact with water (m^2), and t is time (min).

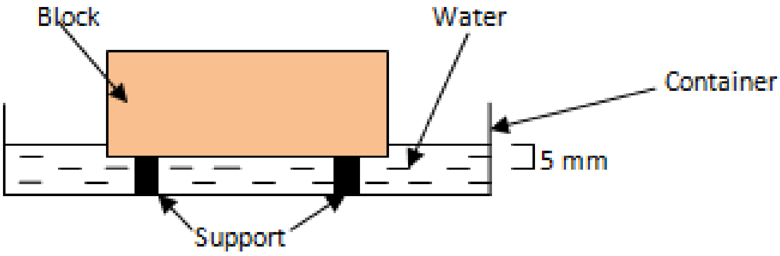


Figure 8.5: Schematic set-up for water absorption by capillary

8.2.3.2 Mechanical properties

Two tests were conducted to determine the mechanical properties of the enhanced soil blocks; these are compressive strength and tensile splitting strength tests. The purpose of conducting these tests and the processes used can be found in Sections 7.2.4.1 and 7.2.4.2 for compressive strength and tensile strength, respectively.

8.2.3.3 Durability properties

Wetting and drying (wearing) and wire brush (erosion) tests were conducted to determine the durability properties of the enhanced soil blocks.

Wetting and drying test

This test was conducted to determine the abrasion resistance of specimen after repeated wetting and drying conditions. The purpose of this test was to find out the ability of the enhanced soil blocks to resist wearing that can be caused by the users, environment and the weather. The test was conducted in accordance with American Society for Testing and Materials ASTM D559-03 (2003). Each block was immersed in water bath for 2 min, removed and dried in an oven at a 105°C temperature for 24 hr. Eighteen vertical wire brush strokes of approximately 13.3 N force for each stroke were applied to each side of the block (Figure 8. 6) and four strokes to each end completing a cycle for 12 cycles. The wearing performance of the blocks was expressed as Equation 8.6.

Figure 8.6: Wire scratch brush test set-up

$$W = \frac{Im - Fm}{Fm} \times 100 \qquad (8.6)$$

Where: W is wearing (%), I_m is initial mass (g), and F_m is final mass of blocks after 12 cycles (g).

Erosion test (Pressure spray method)

The pressure spray test was conducted to determine the resistance of the specimen to continuous rainfall condition. This method was used instead of drip (Geelong) method because it is more representative of the field conditions such as rainfall. The test is an empirical one developed by the former National Building Technology Centre (now Commonwealth Scientific and Industrial Research Organisation (CSIRO) – Australia). The purpose of performing this test was to determine the ability of the blocks to resist erosion which may be caused by continuous rainfall.

The test was conducted in accordance with New Zealand Standard (NZS 4298, 1998). The test rig (Figure 8.7) was set up with shield board positioned in the plastic bath and the pressure spray nozzle set on the bath at a distance 470 mm from the shield. Each block was mounted behind a thin shield and was exposed to spray through a 100 mm diameter hole. The shield ensured that only limited area of the block face was subject to water spray. Tap water was connected to the pressure spray nozzle and then opened at pressure 50 kPa through the nozzle onto the block. The water was sprayed onto the block and run out through the outlet. The spray was stopped at every 15 min to allow for assessment. The depth of pitting was measured using a 10 mm diameter flat ended rod. The rate of erosion was expressed as the pitting depth (mm) per minute of exposure to the spray water.

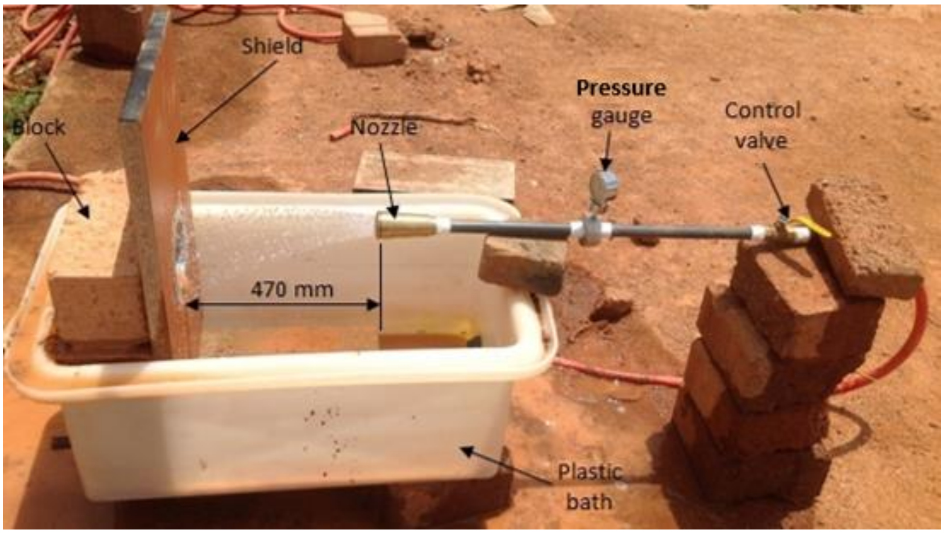


Figure 8.7: Water spray test set-up

8.2.4 Statistical analysis

Correlations were carried-out to establish relationships between properties measured. As each test was to a different sample, conventional pairwise comparisons were not possible; instead, the mean results were used and ranges noted. Two-way ANOVA tests (with Minitab Version 16) were used to test for significant difference and variation between the effects of soil and fibre type.

8.3 RESULTS AND DISCUSSION

The results of this study are presented and discussed under three sub-headings: (1) physical properties, (2) mechanical properties and (3) durability properties.

8.3.1 Physical properties

The physical properties of the fibre reinforced blocks were determined by dry density, water absorption and linear shrinkage tests. Details of the results are provided in Appendix G. Summary of the results obtained from dry density test are presented in Figures 8.8 and 8.9 for soil R and soil B, respectively. It can be seen from both figures that the density of the reinforced soil blocks decresed with increasing fibre contents. There reduction in density was between 7 - 9% for soil R and 6 - 8% for soil B. Similar trends were seen in previous studies (Chan, 2011, Demir, 2006, Danso et al., 2015b) of reinforced soil blocks/bricks with other natural fibres. The drop in density was expected as fibres have low density of 810 – 500 kg/m^3 compared to compressed soil density of about 1780 kg/m^3, and therefore increase fibre content displaced soil content, which is heavier, so decreased the density of the blocks. Soil R blocks had higher density than soil B blocks, which might be due to the higher clay content.

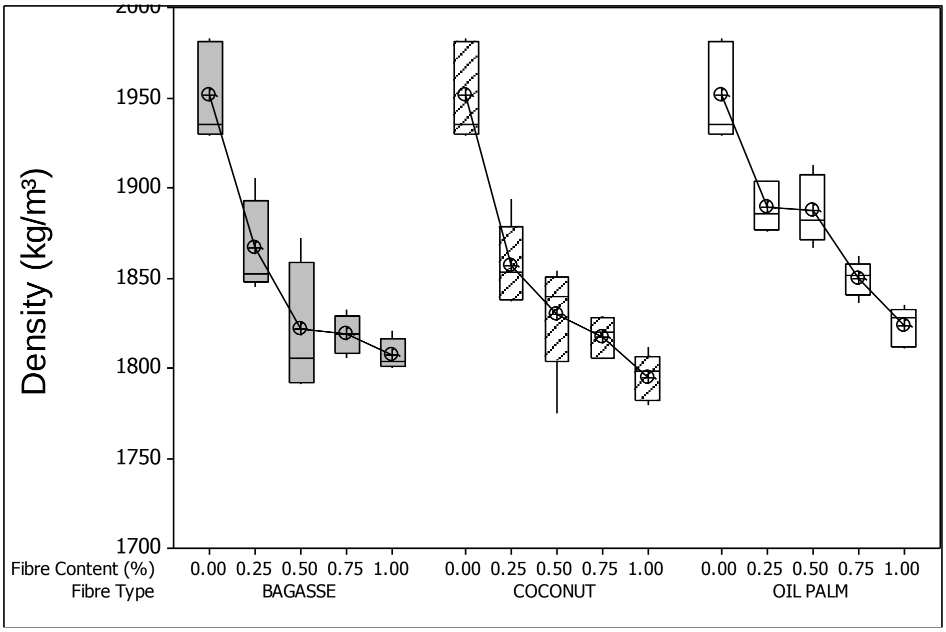


Figure 8.8: Dry density of soil R
Box plots represent the inter-quartile range of data obtained

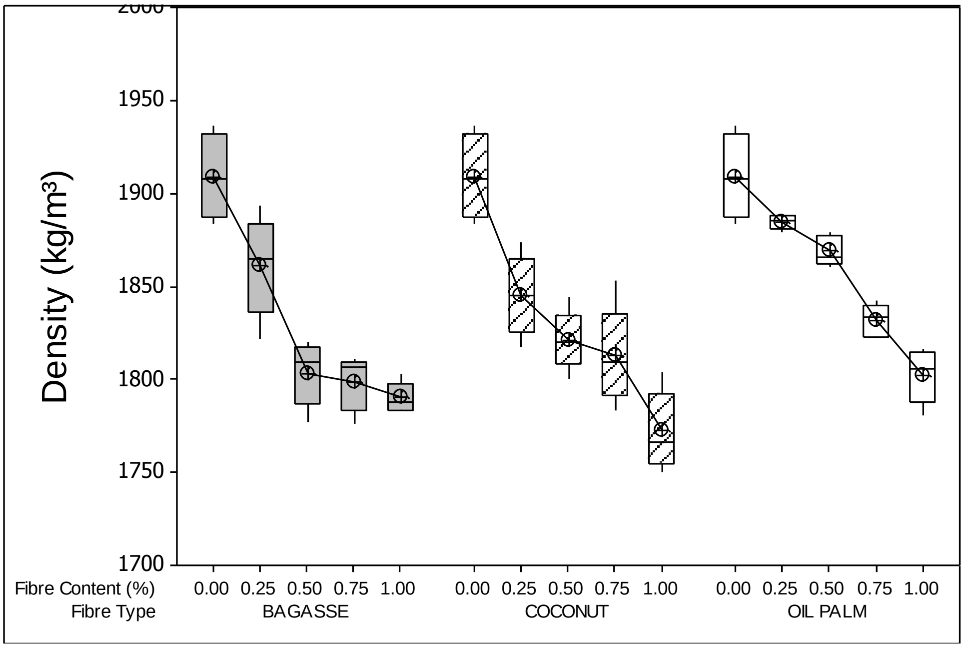


Figure 8.9: Dry density of soil B
Box plots represent the inter-quartile range of data obtained

The water absorption by capillary test results are shown in Figures 8.10 and 8.11, respectively for soil R and soil B. In both figures, the rate of water absorption of the reinforced soil blocks increased with increase fibre content and seems to level off at higher fibre content. This results is consistent with the result of the study by Ismail and Yaacob (2011) which also recorded increase in water absorption of laterite bricks with increase in oil-palm empty-fruit-bunch fibre content. The increase may be attributed to the amount of water absorbed by the cellulose of the fibres, which is due to the void volume and the amount of cellulose material present in the blocks (Jeefferie, 2011). The absorbent nature of fibres creates pathway through soil blocks, thereby allowing more water to be absorbed by the blocks (Danso et al., 2015a, Ghavami et al., 1999, Danso et al., 2015d).

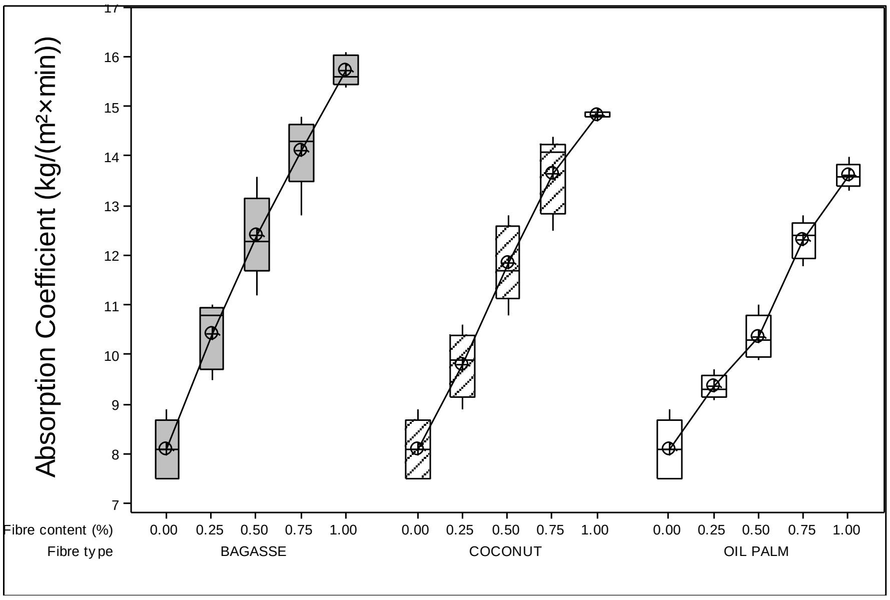


Figure 8.10: Water absorption of soil R

Box plots represent the inter-quartile range of data obtained

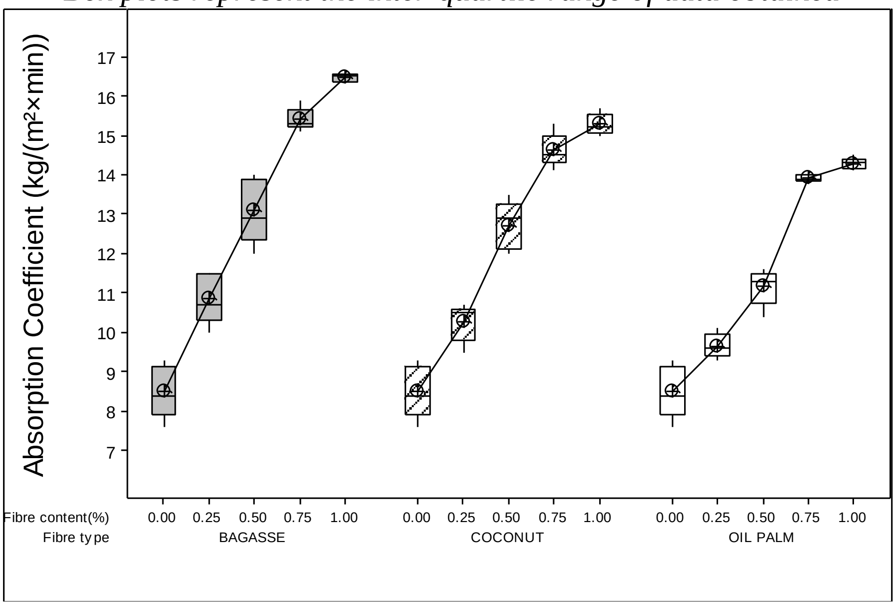


Figure 8.11: Water absorption of soil B

Box plots represent the inter-quartile range of data obtained

Figures 8.12 and 8.13 show the linear shrinkage test results of the enhanced soil blocks for soil R and soil B, respectively. The results indicate that the linear shrinkage of the enhanced soil blocks decreased with increase fibre content. Bouhicha et al. (2005) observed a similar effect which enhanced the properties of soil blocks with barley straw. The addition of the fibres reduces the shrinkage as the fibres oppose the deformation of the soil matrix through friction and/or adhesion. In addition, soil B blocks recorded better shrinkage resistance than soil R blocks, which can be attributed to the lower OMC of the soil. Another contributing factor is the plasticity index, as soil B with plasticity index of 13.9 had less shrinkage. Walker (1995) found that soil with a plasticity index of <20 will have lower linear shrinkage, compared to a plasticity index >20, so this is consistent with published findings.

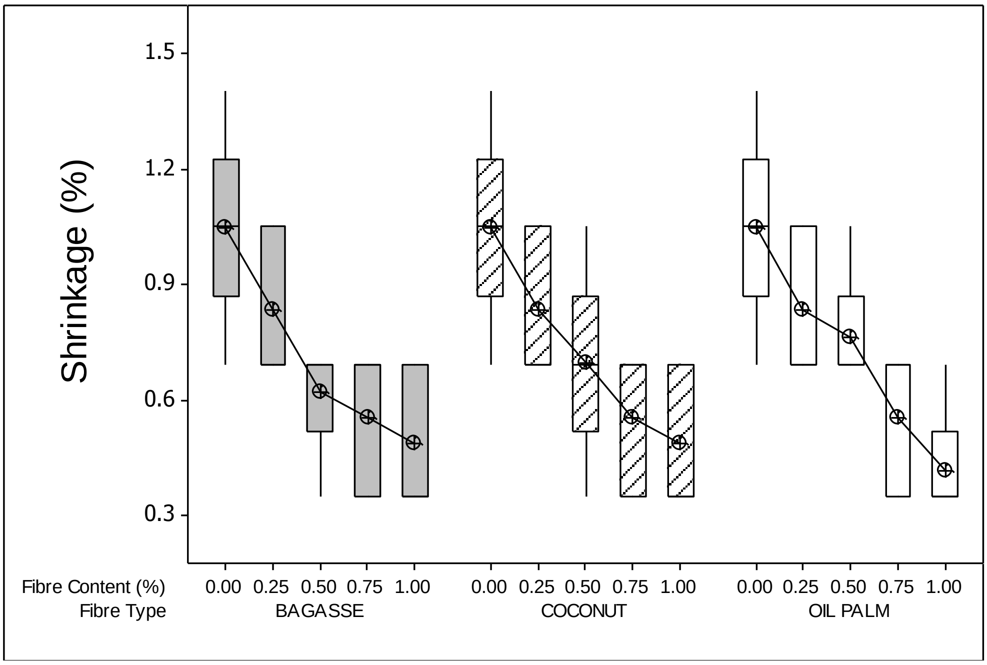


Figure 8.12: Linear shrinkage of soil R
Box plots represent the inter-quartile range of data obtained

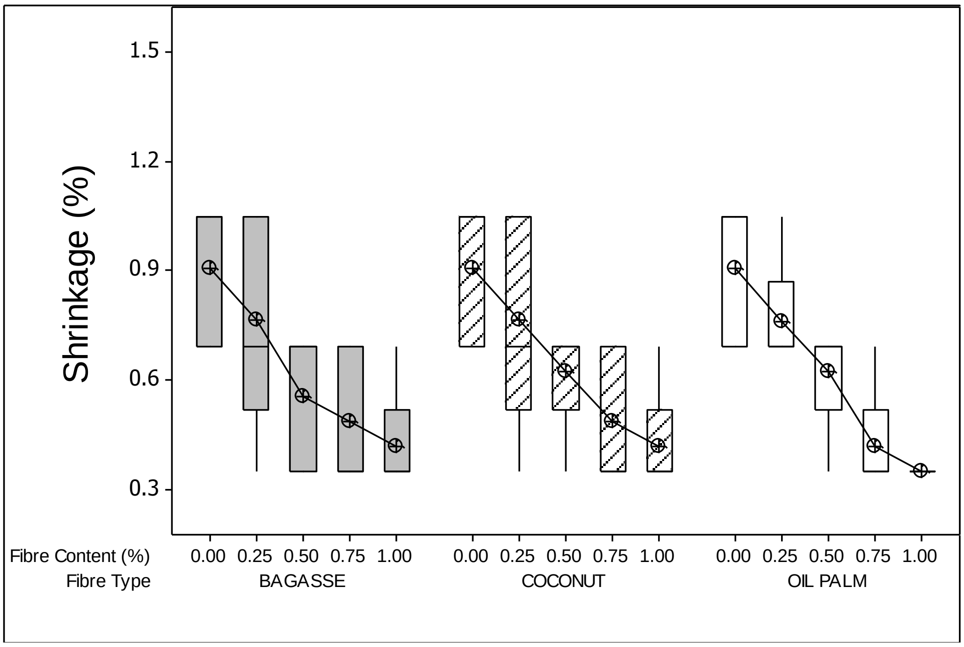


Figure 8.13: Linear shrinkage of soil B
Box plots represent the inter-quartile range of data obtained

8.3.2 Mechanical properties

The mechanical properties of the fibre reinforced soil blocks were determined with compressive strength and splitting tensile strength tests. Details of the results are provided in Appendix H. The compressive strength of the reinforced soil blocks increased with fibre content until it reached between 0.25wt% and 0.5wt% fibre content, and then started declining as presented in Figures 8.14 and 8.15, respectively for soil R and soil B. This indicates an optimum strength. This trend is consistent with previous studies (Akbulut et al., 2007, Bouhicha et al., 2005, Ismail and Yaacob, 2011, Millogo et al., 2014) which used other fibres in soil blocks where an optimum strength has been followed by a subsequent decline at higher fibre inclusions.

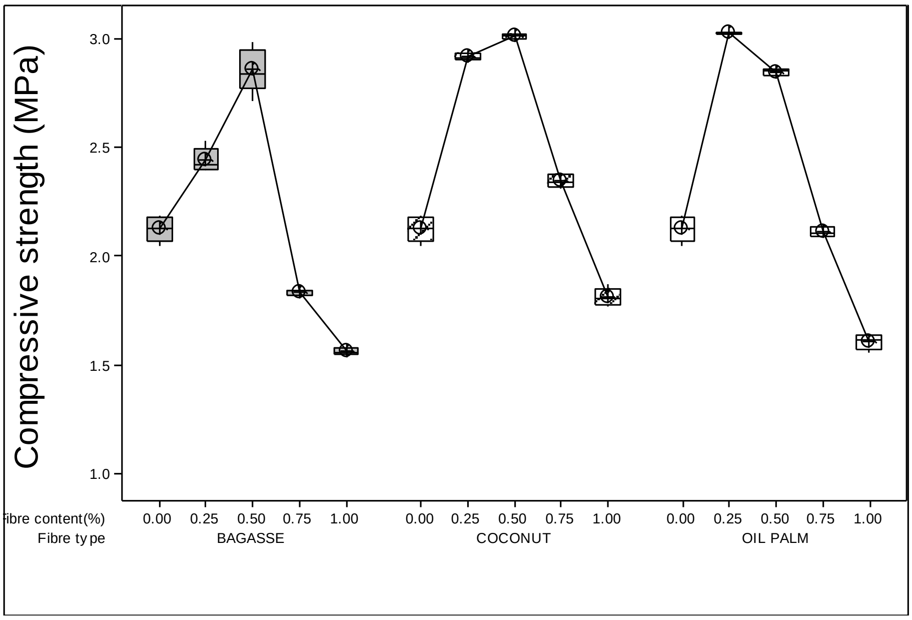


Figure 8.14: Compressive strength of soil R
Box plots represent the inter-quartile range of data obtained

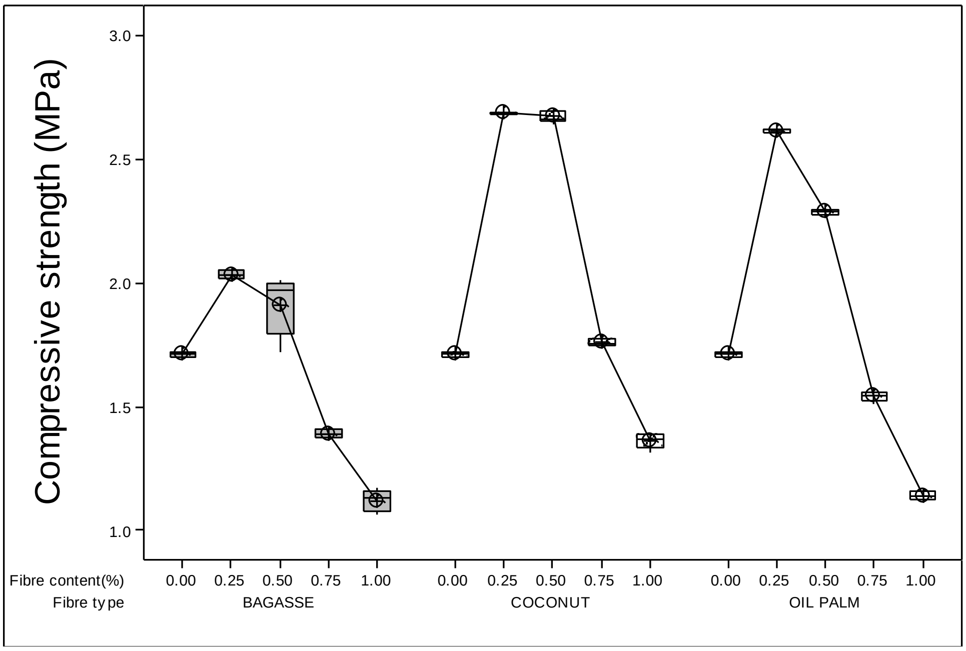


Figure 8.15: Compressive strength of soil B
Box plots represent the inter-quartile range of data obtained

The increase in compressive strength from unreinforced soil blocks to the optimum was up to 42%, 41% and 39%, respectively for oil palm, coconut and bagasse fibres reinforced soil blocks for soil R. While the increase for soil B was 53%, 57% and 18%, respectively for oil palm, coconut and bagasse fibres reinforced soil blocks. Soil R obtained better optimum strength than soil B reinforced soil blocks, while soil B obtained the highest increase of reinforced over the unreinforced blocks. The increase in strength could be linked to increase friction between the fibre and the soil matrix. Furthermore, the association of fibres and the soil matrix prevents the spread of cracks in the blocks, as fibres form bridges across cracks and therefore contribute to the improved strength. Conversely, after a critical point, the increase fibre content caused strength reduction when fibres begin to knot and overlap each other (Ismail and Yaacob, 2011) resulting in reduced cohesion with the soil (Medjo Eko et al., 2012) and break-up of the soil matrix (Millogo et al., 2014) causing the soil-fibre composite to weaken. It is also likely that the presence of more pores due to increase fibre content in the soil matrix could lead to the reduction in strength.

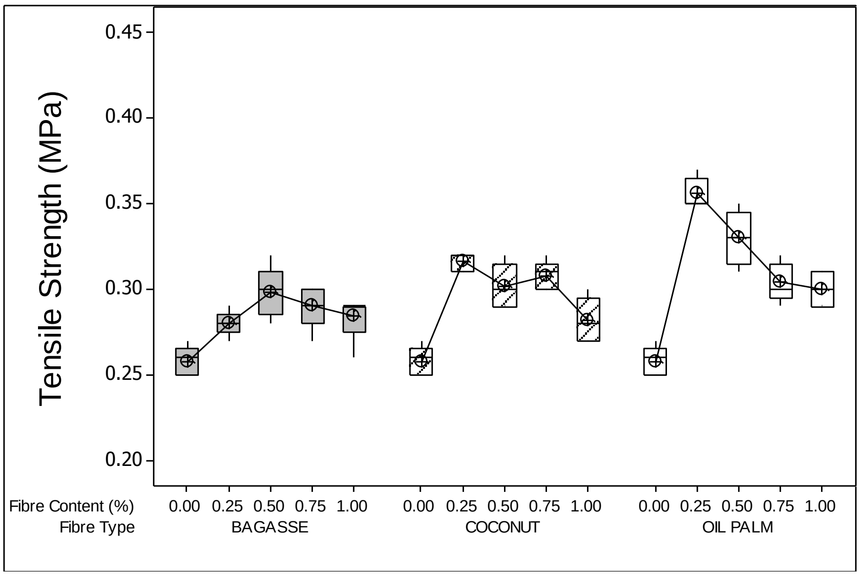


Figure 8.16: Tensile strength of soil R
Box plots represent the inter-quartile range of data obtained

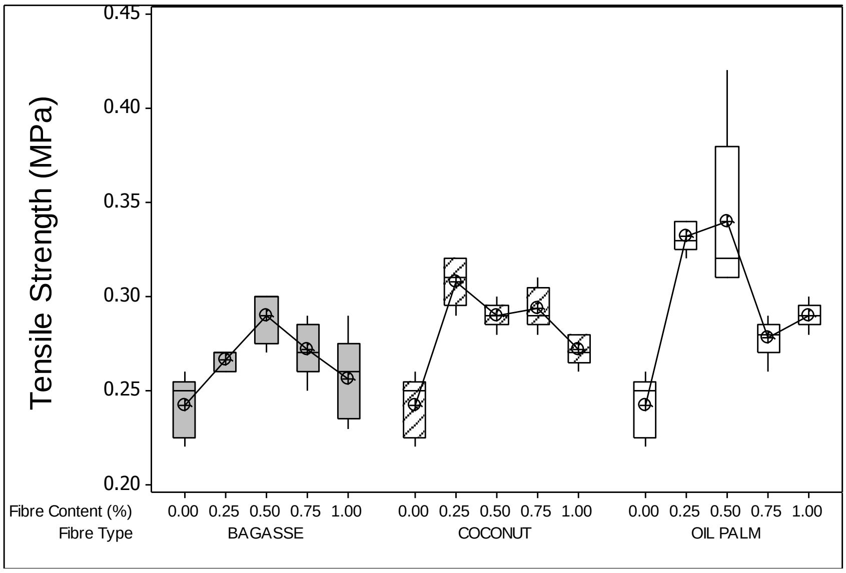


Figure 8.17: Tensile strength of soil B
Box plots represent the inter-quartile range of data obtained

Tensile strength test results are reported in Figures 8.16 and 8.17 for soil R and soil B respectively. It can be seen that the tensile strength also displays an optimum fibre content between 0.25wt% and 0.5wt%. The optimum points are similar for both compressive and tensile strength.

The reinforced soil blocks recorded about 35%, 23% and 16% mean tensile strength increase over the unreinforced at optimum, respectively for oil palm, coconut and bagasse for soil R. While soil B obtained 38%, 29% and 21% increase, respectively for oil palm, coconut and bagasse. It was observed that failure of unreinforced blocks was sudden and produced only one large crack, while the failure of the fibre reinforced soil blocks was with multiple finer cracks (Figure 8.18). This means the failure was more gradual, acting more like a ductile than a brittle material, which agrees well with the findings of Bouhicha et al. (2005), Cai et al. (2006) and Danso et al. (2015c). Upon removal of the blocks from the testing machine, though they were split into two, the two parts were still held together by the fibres. This indicates that fibre reinforced blocks will fail slowly rather than suddenly and will still hold a load for some time after failure, though with considerable deformation.

Unreinforced block Reinforced block

Figure 8.18: Failure of soil blocks under tensile force

Although compressive and tensile strengths increased together (Figure 8.19), none of the correlations for each fibre and soil type were significant (0.170>p>0.686). Indicating that while generally a block that is strong in compression will also be strong in tension, compressive testing is a poor predictor of tensile strength. This is in contrast to other studies such as those summarised by Walker (2004) which reports better correlations of tensile and compressive strengths. However, the linear models for the coconut and oil palm fibres explained more of the variation (0.720>r>0.625) than for the bagasse (0.315 >r>0.249) which may be explained by the rougher texture of bagasse fibres (see Figure

5.14 under Section 5.5.5) and the lower tensile strength of the fibres. The scaling factor of the correlation is also higher than many previous studies with factors of between 6.6 and 14.9 being apparent from the gradient (*m*) of the linear fits.

The effectiveness of the enhancement was more pronounced with soil R than soil B in both compressive and tensile strengths, which may be primarily attributed to the higher clay content, improving bonding between fibres and the matrix. Another contributing factor is the higher OMC of soil R which aided the increased mechanical strength development of the blocks. Bagasse fibre reinforced soil blocks obtained the lowest strength, coconut and oil palm performed similarly in compression, but oil palm performed better in tension. This may be explained by the high tensile strength (see Table 5.4 under Section 5.5.4) of coconut and oil palm fibres.

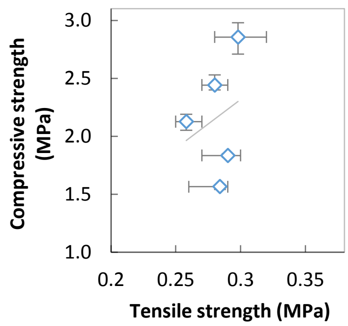
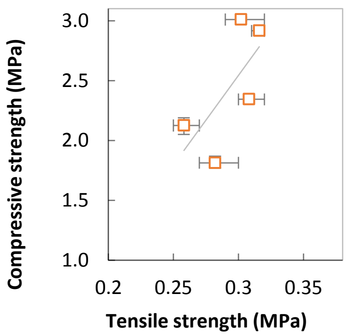
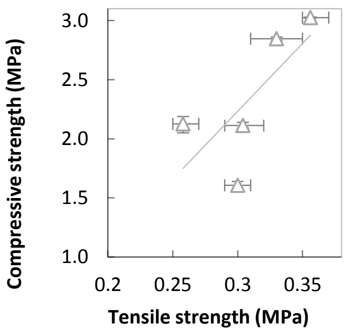
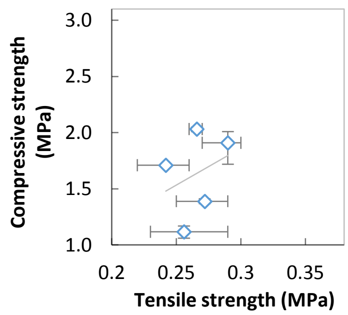
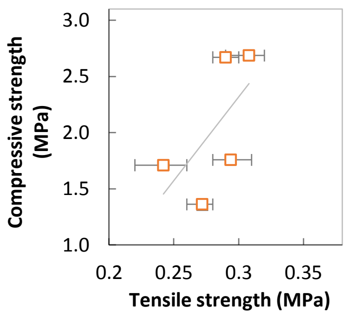
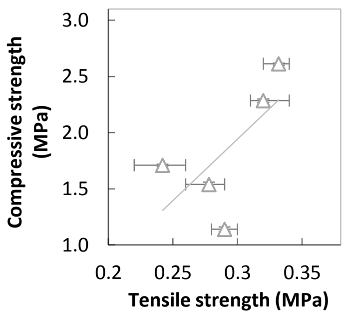
Soil		**Fibre**		
		Baggasse	**Coconut**	**Oil Palm**
Red				
	m	8.39	14.9	11.5
	r	0.249	0.679	0.720
	p	0.686	0.207	0.170
Brown				
	m	6.61	14.9	10.9
	r	0.315	0.625	0.660
	p	0.606	0.259	0.226

Figure 8.19: Correlation / regression statistics for compressive vs. tensile strengths

Compressive and tensile strength test results were subjected to a Two-way ANOVA to determine whether fibre selection or soil selection is more important. The values used are those for the nominal optimum of 0.5wt% fibre contents for the three fibre types and the two soil types. The results obtained are presented in Figure 8.20 and show a greater variation in the compressive strength than tensile strength for both fibre and soil treatments. The ANOVA results indicate that for compressive strength, soil type (F = 540) is on the average dominant over fibre type (F = 227). On the other hand, tensile strength results suggest that the fibre type (F = 17) is dominant over soil type (F = 4). This can be explained that soil blocks without fibres can perform better under compression than tensile, this is because soil in its natural state has some good compressive resistance but have poor resistance against tensile. Therefore, the inclusion of fibres (which have good tensile strength) contribute greatly in the tensile performance of the blocks. In Figure 8.18, it was observed that when the soil matrix fails and the fibres will still be connecting the broken parts together, which implies the compressive failure of the blocks are affected greatly by the soil while the fibres will still act against splitting of the blocks. In both tests, statistically significant differences were found with $p < 0.05$.

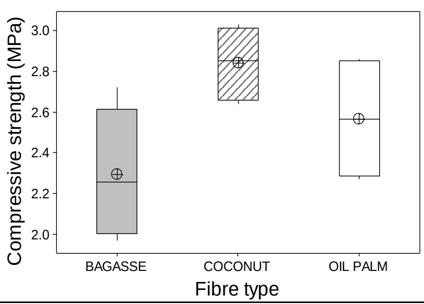
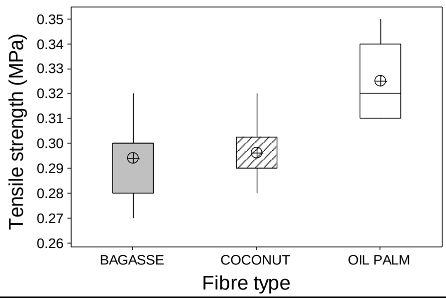
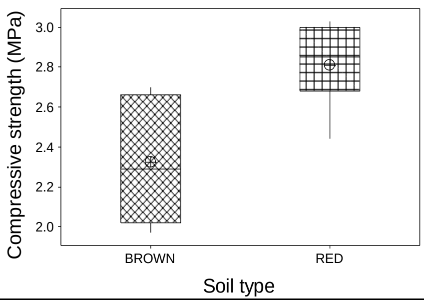
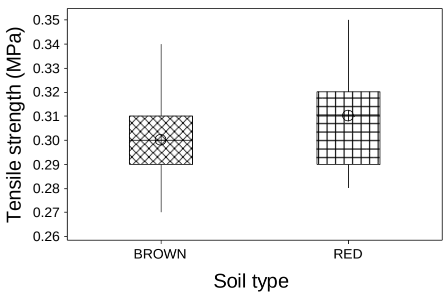
<table>
<tr><th></th><th>Compressive strength</th><th>Tensile strength</th></tr>
<tr><td>Fibre type</td><td>
</td><td>
</td></tr>
<tr><td>Soil type</td><td>
</td><td>
</td></tr>
<tr><td>ANOVA results (soil vs. fibre types)</td><td>
<table>
<tr><th>Source</th><th>DF</th><th>SS</th><th>MS</th><th>F</th><th>P</th></tr>
<tr><td>Soil type</td><td>1</td><td>1.786</td><td>1.786</td><td>540.15</td><td>0.000</td></tr>
<tr><td>Fibre type</td><td>2</td><td>1.502</td><td>0.751</td><td>227.04</td><td>0.000</td></tr>
<tr><td>Interaction</td><td>2</td><td>0.082</td><td>0.041</td><td>12.42</td><td>0.000</td></tr>
<tr><td>Error</td><td>24</td><td>0.079</td><td>0.003</td><td></td><td></td></tr>
<tr><td>Total</td><td>29</td><td>3.449</td><td></td><td></td><td></td></tr>
</table>
S = 0.05750 R-Sq = 97.70% R-Sq(adj) = 97.2%</td><td>
<table>
<tr><th>Source</th><th>DF</th><th>SS</th><th>MS</th><th>F</th><th>P</th></tr>
<tr><td>Soil type</td><td>1</td><td>0.001</td><td>0.001</td><td>4.33</td><td>0.048</td></tr>
<tr><td>Fibre type</td><td>2</td><td>0.006</td><td>0.003</td><td>17.37</td><td>0.000</td></tr>
<tr><td>Interaction</td><td>2</td><td>0.000</td><td>0.000</td><td>0.06</td><td>0.944</td></tr>
<tr><td>Error</td><td>24</td><td>0.004</td><td>0.001</td><td></td><td></td></tr>
<tr><td>Total</td><td>29</td><td>0.011</td><td></td><td></td><td></td></tr>
</table>
S = 0.01317 R-Sq = 62.01% R-Sq(adj) = 54.09%</td></tr>
</table>

Figure 8.20: Two-way ANOVA statistics for fibre vs. soil types (compressive and tensile)

Box plots represent the inter-quartile range of data obtained

8.3.3 Durability properties

The durability of the fibre reinforced soil blocks were investigated by the use of wearing and erosion tests. Details of the results are provided in Appendix I. Results of the wearing test are presented in Figures 8.21 and 8.22, respectively for soil R and soil B. It can be seen that there was a rapid reduction in wearing of the blocks up to 0.5wt% fibre content, after which the wearing rate levels off or reverses slightly with further fibre inclusion. The greatest reduction in wearing as compared to unreinforced soil blocks was 20%, 38% and 33%, respectively for oil palm, coconut and bagasse fibres reinforced soil blocks for soil R. While the reduction for soil B was 47%, 50% and 47%, respectively for oil palm, coconut and bagasse fibres reinforced soil blocks. This implies that the inclusion of fibres in the soil blocks will increase the resistance of the blocks against wearing caused by external factors such as wind and human/animal activities.

It should be noted that reduction in wearing after the optimum of 0.5wt% fibre content has a comparatively small effect, allowing blocks to be made with a reasonable range of fibre contents without significant deviation from optimum wearing resistance. Similarly, a study with cement as stabiliser by Yalley (2012) recorded increase in abrasion (wearing) resistance with cement increase up to 4%, after which there was no increase with further addition of cement content.

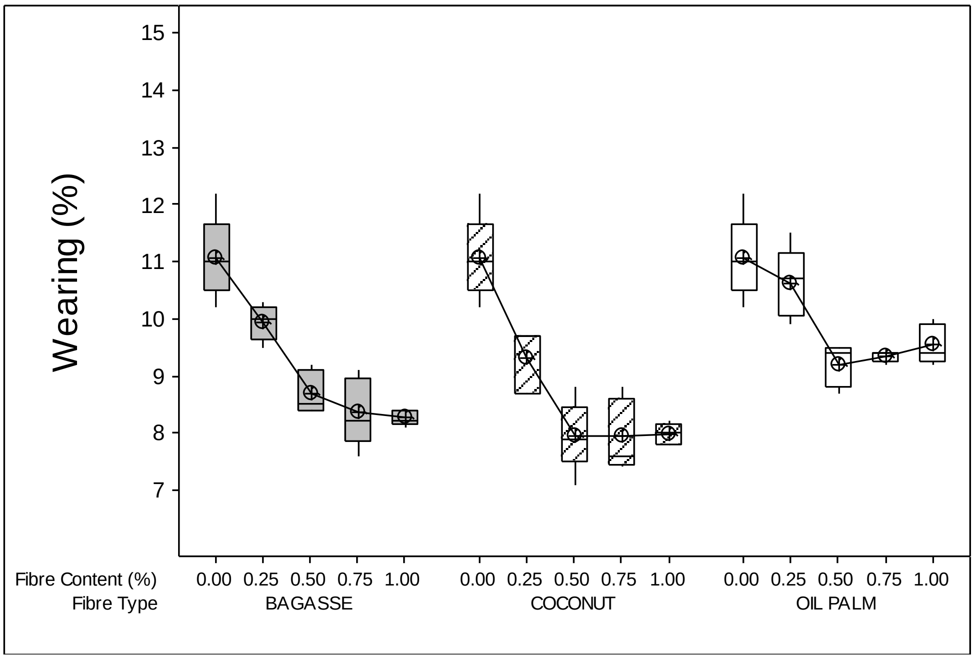


Figure 8.21: Wearing of soil R

Box plots represent the inter-quartile range of data obtained

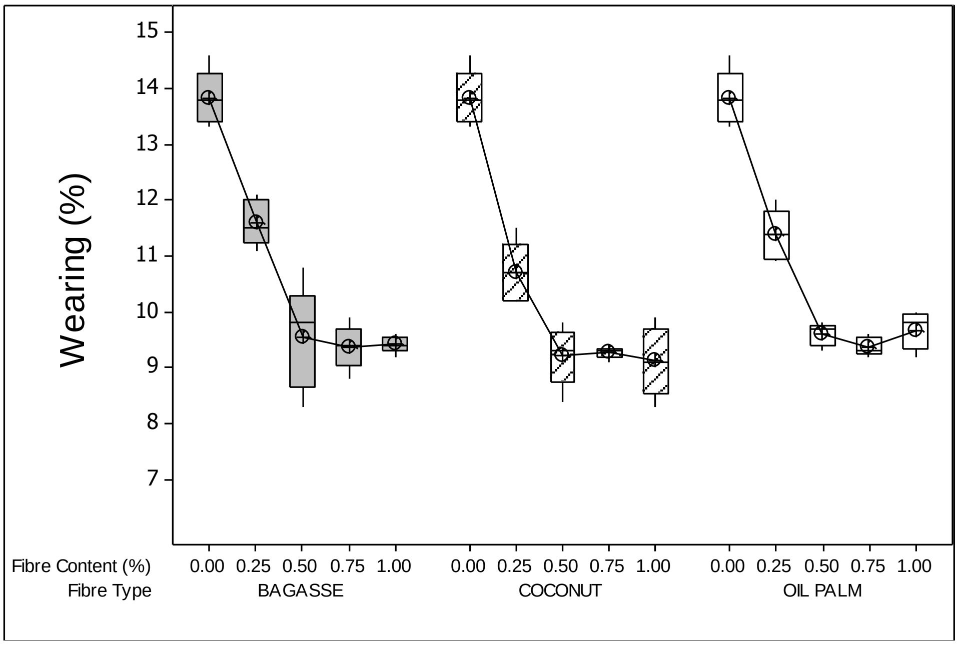


Figure 8.22: Wearing of soil B
Box plots represent the inter-quartile range of data obtained

The results presented in Figures 8.23 and 8.24 show the same rapid reduction in erosion with increase fibre content up to 0.5wt% as found in the wearing results, then levels off and increases slightly after 0.75% fibre content for both soil types. There was between 50 – 70% and 44 – 50% reduction, respectively for soil R and soil B in the erosion for fibre reinforced soil blocks as compare to the unreinforced.

The increase resistance of the reinforced soil blocks can be explained by the fibres ability to shield the soil particles from been washed away by water, thereby reducing the eroding effect on the blocks. The behaviour of the fibres in the soil is similar to tree roots protecting earth from erosion by holding the earth within its boundary (Huat and Kazemian, 2010, Michalowski and Zhao, 1996). This test is particularly important, particularly for high rainfall areas where erosion of earth buildings is common. There is, however a requirement to develop more climate-appropriate benchmarks as proposed by Bui et al. (2009).

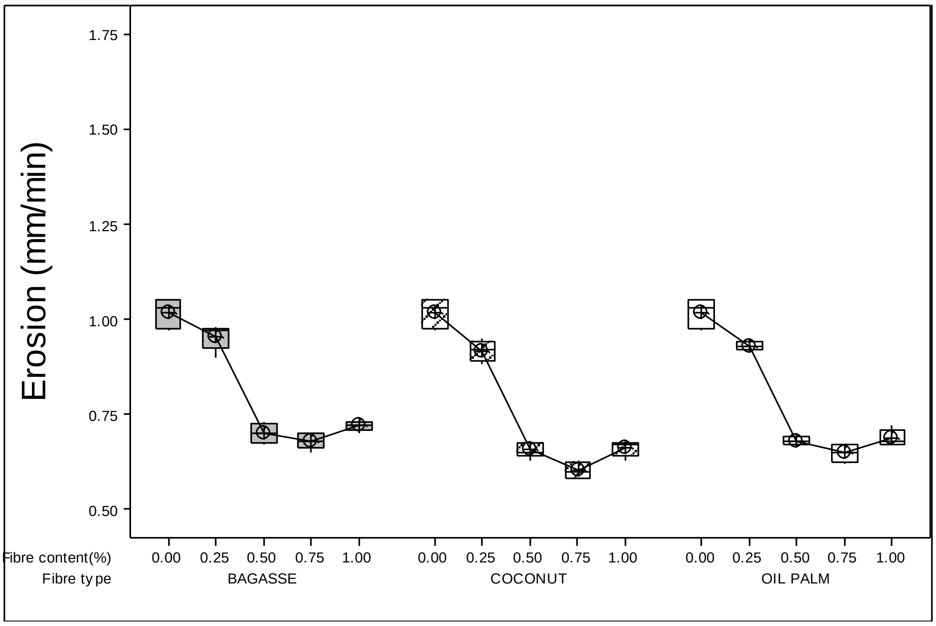


Figure 8.23: Erosion of soil R

Box plots represent the inter-quartile range of data obtained

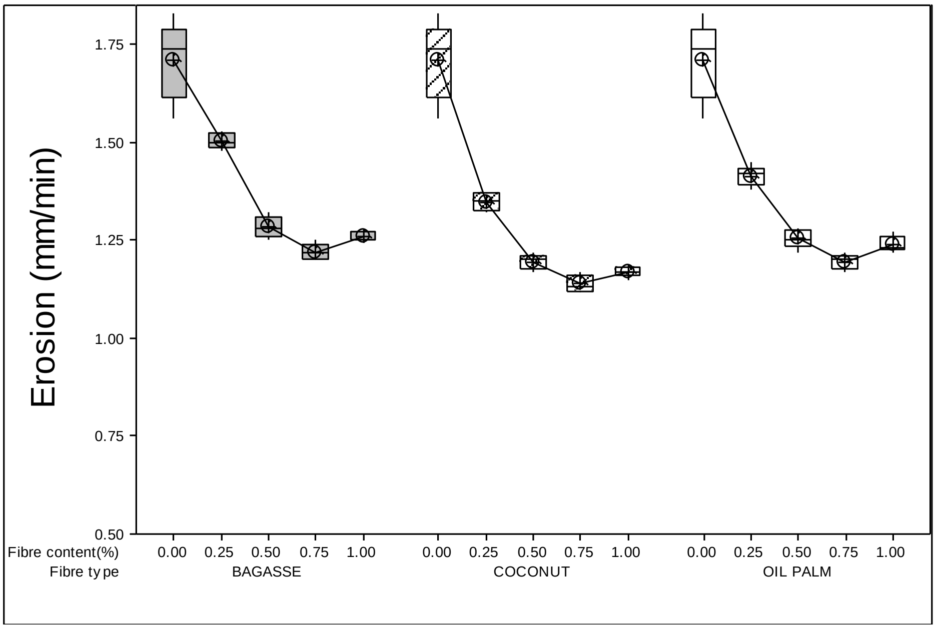


Figure 8.24: Erosion of soil B

Box plots represent the inter-quartile range of data obtained

The correlation/regression between wearing and erosion tests are presented in Figure 8.25, which display excellent correlation between the measures with $0.997 > r > 0.955$ and $0.00018 < p < 0.011$. This suggests that it is possible to ascertain the durability of blocks with just one of these tests.

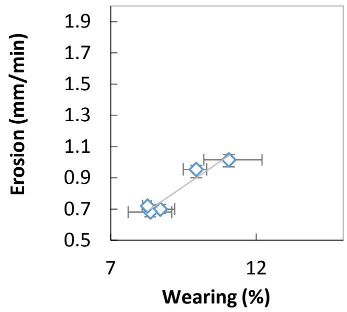
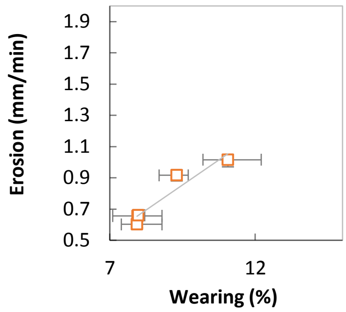
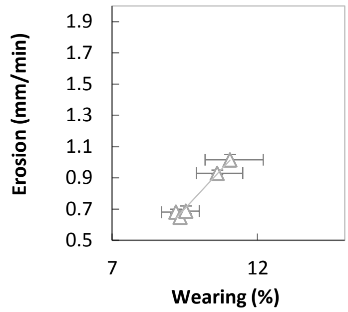
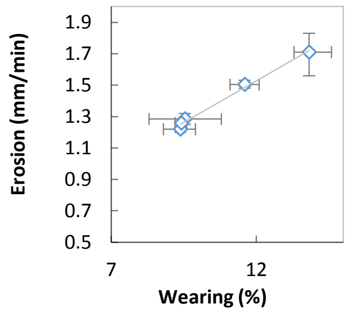
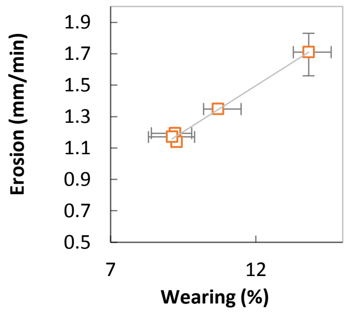
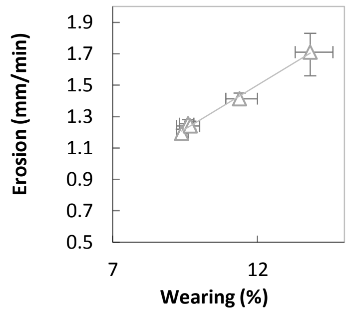
<table>
<tr><th rowspan="2">Soil</th><th colspan="3">Fibre</th></tr>
<tr><th>Baggasse</th><th>Coconut</th><th>Oil Palm</th></tr>
<tr><td>Red</td><td></td><td></td><td></td></tr>
<tr><td>m</td><td>0.127</td><td>0.129</td><td>0.200</td></tr>
<tr><td>r</td><td>0.965</td><td>0.955</td><td>0.989</td></tr>
<tr><td>p</td><td>0.0078</td><td>0.0110</td><td>0.0013</td></tr>
<tr><td>Brown</td><td></td><td></td><td></td></tr>
<tr><td>m</td><td>0.106</td><td>0.118</td><td>0.112</td></tr>
<tr><td>r</td><td>0.995</td><td>0.995</td><td>0.997</td></tr>
<tr><td>p</td><td>0.0004</td><td>0.0004</td><td>0.0002</td></tr>
</table>

Figure 8.25: Correlation / regression statistics for erosion vs. wearing

A number of studies (Venkatarama Reddy and Jagadish, 1995, Walker, 2004) have suggested that physical properties such as mechanical strength or density may be used as proxy measures for durability for blocks stabilised using binders. To see if this also holds for fibre reinforced blocks, correlation and regression tests were performed on compression and tensile strengths compared to wearing, density to wearing and water absorption to erosion.

The results of the strength correlations are presented in Table 8.3 and the physical correlations in Table 8.4. Mechanical properties are, unfortunately very poorly correlated to wearing with both positive and negative relations, $-0.280 < r < 0.428$ and poor significance, $0.059 < p < 0.870$. The relationships of physical properties to durability are in stark contrast with recommendations for binder stabilised blocks. In binder stabilised blocks, physical properties positively correlate highly with durability properties, but this is not the case with fibre reinforced soil blocks.

Table 8.3: Correlation of strength vs wearing

Test		Fibre		
		Baggasse	**Coconut**	**Oil Palm**
Tensile vs wearing				
Red soil	*m* (MPa/%)	-0.011	-0.106	-0.012
	r	-0.864	-0.620	-0.280
	p	0.059	0.265	0.265
Brown soil	*m* (MPa/%)	-0.006	-0.009	-0.009
	r	-0.697	-0.682	-0.519
	p	0.191	0.204	0.370
Compressive vs wearing				
Red soil	*m* (MPa/%)	0.108	-0.047	0.102
	r	0.258	-0.127	-0.280
	p	0.676	0.839	0.816
Brown soil	*m* (MPa/%)	0.083	-0.031	0.052
	r	0.428	-0.102	0.165
	p	0.472	0.870	0.791

Table 8.4: Correlation of physical vs durability properties

Test		Fibre		
		Baggasse	Coconut	Oil Palm
Density vs. wearing				
Red soil	*m* (%/(kg/m^3))	48.20	43.30	43.70
	r	0.978	0.971	0.751
	p	0.004	0.006	0.143
Brown soil	*m* (%/(kg/m^3))	26.10	23.50	18.10
	r	0.994	0.936	0.801
	p	0.001	0.019	0.100
Water absorption vs. erosion				
Red soil	*m* ((mm/min)/%)	-0.047	-0.061	-0.064
	r	-0.888	-0.916	-0.845
	p	0.044	0.029	0.071
Brown soil	*m* ((mm/min)/%)	-0.060	-0.075	-0.071
	r	-0.943	-0.905	-0.857
	p	0.016	0.035	0.064

As with the mechanical properties, wearing and erosion test results were subjected to a Two-way ANOVA to determine whether fibre selection or soil selection is more important for durability. The results obtained are presented in Figure 8.26 and show fibre type actually making very little difference (F = 2.80 for wearing and 1.53 for erosion and with p < 0.05 in both cases) but soil dominating, particularly for erosion (F = 358, p < 0.005). The effectiveness of the enhancement was more pronounced with soil R (high clayey soil) than soil B (low clayey soil) in both wearing and erosion. This may be attributed to the high clay content of soil R (see Section 4.5.2). As clay act as binder in the matrix, it holds the other constituent together, making it difficult from being blown and washed away.

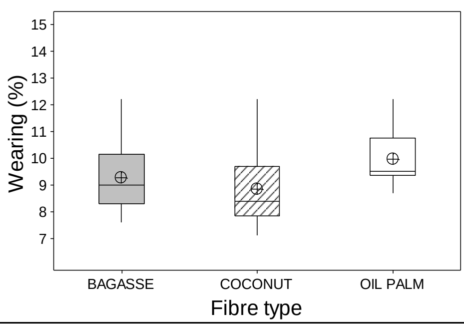
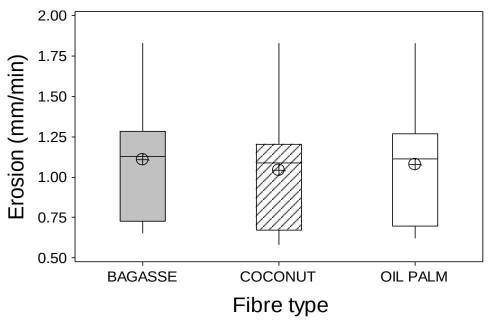
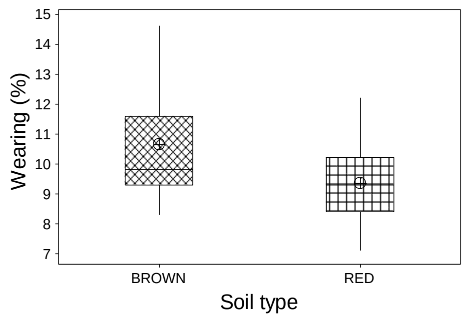
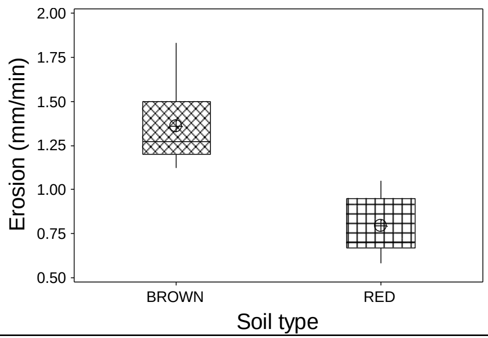
<table>
<tr><th></th><th>Wearing</th><th>Erosion</th></tr>
<tr><td>Fibre type</td><td>
</td><td>
</td></tr>
<tr><td>Soil type</td><td>
</td><td>
</td></tr>
<tr><td>ANOVA results (soil vs. fibre types)</td><td>
<table>
<tr><th>Source</th><th>DF</th><th>SS</th><th>MS</th><th>F</th><th>P</th></tr>
<tr><td>Soil type</td><td>1</td><td>62.986</td><td>62.99</td><td>26.94</td><td>0.000</td></tr>
<tr><td>Fibre type</td><td>2</td><td>13.107</td><td>6.55</td><td>2.80</td><td>0.064</td></tr>
<tr><td>Interaction</td><td>2</td><td>4.301</td><td>2.15</td><td>0.92</td><td>0.401</td></tr>
<tr><td>Error</td><td>144</td><td>336.73</td><td>2.34</td><td></td><td></td></tr>
<tr><td>Total</td><td>144</td><td>417.12</td><td></td><td></td><td></td></tr>
</table>
S = 1.529 R-Sq = 19.27% R-Sq(adj)=16.5%</td><td>
<table>
<tr><th>Source</th><th>DF</th><th>SS</th><th>MS</th><th>F</th><th>P</th></tr>
<tr><td>Soil type</td><td>1</td><td>11.95</td><td>11.95</td><td>358.03</td><td>0.000</td></tr>
<tr><td>Fibre type</td><td>2</td><td>0.10</td><td>0.05</td><td>1.53</td><td>0.219</td></tr>
<tr><td>Interaction</td><td>2</td><td>0.01</td><td>0.01</td><td>0.16</td><td>0.856</td></tr>
<tr><td>Error</td><td>144</td><td>4.81</td><td>0.003</td><td></td><td></td></tr>
<tr><td>Total</td><td>144</td><td>16.87</td><td></td><td></td><td></td></tr>
</table>
S = 0.1827 R-Sq = 71.51% R-Sq(adj) = 70.52%</td></tr>
</table>

Figure 8.26: Two-way ANOVA statistics for fibre vs. soil types (wearing and erosion)
Box plots represent the inter-quartile range of data obtained

8.4 SUMMARY

This investigation presented the properties of soil building blocks enhanced with coconut husk fibres, oil palm nut fruit fibres and sugarcane bagasse fibres in a soil that would normally be selected for soil block making and also a soil with a greater clay content. It consisted of materials and methods, results and discussion. Two types of soil and three fibre types were used for the investigation. The tests conducted include density, water absorption, linear shrinkage, compressive strength, splitting tensile strength, wearing and erosion. Correlations among the variables were also carried-out to determine the relationship between the properties. The results were presented and discussed under three main properties: (1) physical, (2) mechanical and (3) durability. The main conclusion of the investigation can be found in Section 12.2. On the basis of the test results obtained from the experiments, the following summary can be made:

- The addition of the agricultural waste fibres to the soil blocks contributed to a reduction in density and linear shrinkage of the blocks, but increased in water absorption. This means that the blocks will contribute to a reduction in weight of structures and have reduced cracking. They will, however allow greater water ingress which may be problematic for damp inside the building, however the ingress does not correlate with increased erosion as would normally be assumed.
- Compressive strength and tensile strength of the reinforced soil blocks were greater than unreinforced soil blocks, and the optimum effectiveness of the enhancement was obtained between 0.25% and 0.5% weight content of the fibres to the soil. The agricultural waste fibres inclusion in soil blocks improved the mechanical properties of the blocks with an increase in strength of between 16% and 57 %. Coconut and oil palm fibre reinforced blocks were more effective than bagasse reinforced soil blocks.
- The use of the agricultural waste fibres as reinforcement in the soil blocks reduced the rate of wearing by 20% to 50% and erosion of the soil blocks by 44% to 70% when subjected to wetting and drying, and water spray tests. The effect of fibre was, however smaller than soil selection. Soil with a high clay content, even with no fibres, outperformed a soil more in-keeping with current recommendations for soil blocks.

- There was a clear strength optimum of 0.25% to 0.5% waste fibre content by weight but the optimum was less critical for durability, which was relatively stable at higher fibre content.
- Attempts to extrapolate mechanical and durability properties from physical properties will result in errors. Unlike binder stabilised blocks, density is inversely correlated with strength and durability. Compressive and tensile strength are positively, but poorly correlated and both unreliably correlated with durability. Water absorption is negatively correlated with erosion.
- Soil type was found to be most important element in compressive strength development with highly clayey soil performing better in most of the tests. While fibre type was the most important element in tensile strength development. Soil was the most important factor in durability with clayey soil performing best, contrary to normal recommendations (Houben and Guillaud, 1994) which are based on the needs of binder stabilised blocks.

CHAPTER 9

9 INTERNAL MECHANISM OF THE FIBRE REINFORCED SOIL MATRIX

9.1 INTRODUCTION

This chapter investigates the internal mechanism of the fibre-soil matrix interactions. Since the enhanced soil blocks are composite materials combining soil and natural fibres, it is necessary to find out what happens within the blocks to better describe the internal properties of the blocks. The chapter therefore aims at determining the distribution of the fibres in matrix, any existence of gaps at the peripheral of the fibres in the matrix and any effect of fibres pull-out on the composite.

9.2 EXPERIMENTAL MATERIALS AND METHODS

9.2.1 Materials

The main materials for the experiment were the soil HI as described in Section 4.2 and the bagasse, coconut and oil palm fibres described in Section 5.2. Tap water from Geotechnics Laboratory of University of Portsmouth was used.

9.2.2 Specimen preparation

Soil, 1% fibre by weight as recommended by previous studies (Obonyo et al., 2010b, Yalley, 2012) and 11.9% water (as obtained by OMC in Section 4.5.1) were used for making the specimens. The soil was first spread on a platform, and then the fibre was spread on soil and turned over and over until a uniform mixture was obtained. Water was sprinkled on the soil-fibre mixture and turned over and again to obtain a homogenous mixture. Cylindrical specimens of 80 mm length × 40 mm diameter (Figure 9.1) were prepared by placing 200 g of the mixture into a cylindrical mould with 40 mm internal diameter and 125 mm length and quasi-statically compressing at 10 MPa pressure to a length of 80 mm, using a close fitting piston with a Tinius Olsen H50KS (Figure 9.2a) as was done in Section 6.2.1. These specimens were used to find out the distribution of the fibres in the soil matrix. 50 mm cube specimens (Figure 9.1) were prepared with a steel mould with internal dimension 50 × 50 × 50 mm and compressed at 10 MPa pressure with a Tinius Olsen H50KS. One mould was placed on the other which allowed the mixture to be placed in and compressed to 50 mm with a wooden plate on top. The cubes were used to determine the gaps between the fibres. All the specimens were dried in fan assisted Genlab electronic oven (Figure 9.2bc) at a temperature of 40°C for five days when the mass stabilised.

Figure 9.1: Cube and cylindrical specimen

Figure 9.2: Preparing specimen
(a) Compressing cylindrical specimen, (b) drying cylindrical specimen (c) drying cube specimen

Soil block specimen of 20 × 20 × 60 mm were prepared with single fibre embedded in each sample for the pull-out test. Four different fibre lengths representing 1/2, 1/4, 1/8 and 1/16 of the total length of each fibre were embedded in the soil matrix leaving the remaining length out of the specimen. Details of the fibre length and diameter are presented in Table 9.1.

Table 9.1: Fibre diameter and length used for pull-out test

Fibre type	Mean ± SD diameter (mm)	Mean ± SD length (mm)	Length embedded in soil matrix (mm)			
			1/2	1/4	1/8	1/16
Bagasse	0.78±0.19	110±28.93	55	28	14	7
Coconut	0.40±0.17	103±17.94	52	26	13	6
Oil palm	0.38±0.08	38±5.84	19	10	5	3

One hundred fibres (from each fibre type) were randomly selected for determining the length and diameter as described in Section 5.4.1

The specimen were made with a steel mould and a presser with 1 mm hole drilled in the middle to keep the fibre outside the soil (Figure 9.3), and then pressed with Tinius Olsen H50KS at 10 MPa pressure. The specimen were then pressed out of the mould and allowed to air dry (Figure 9.4) for three weeks when the mass stabilised.

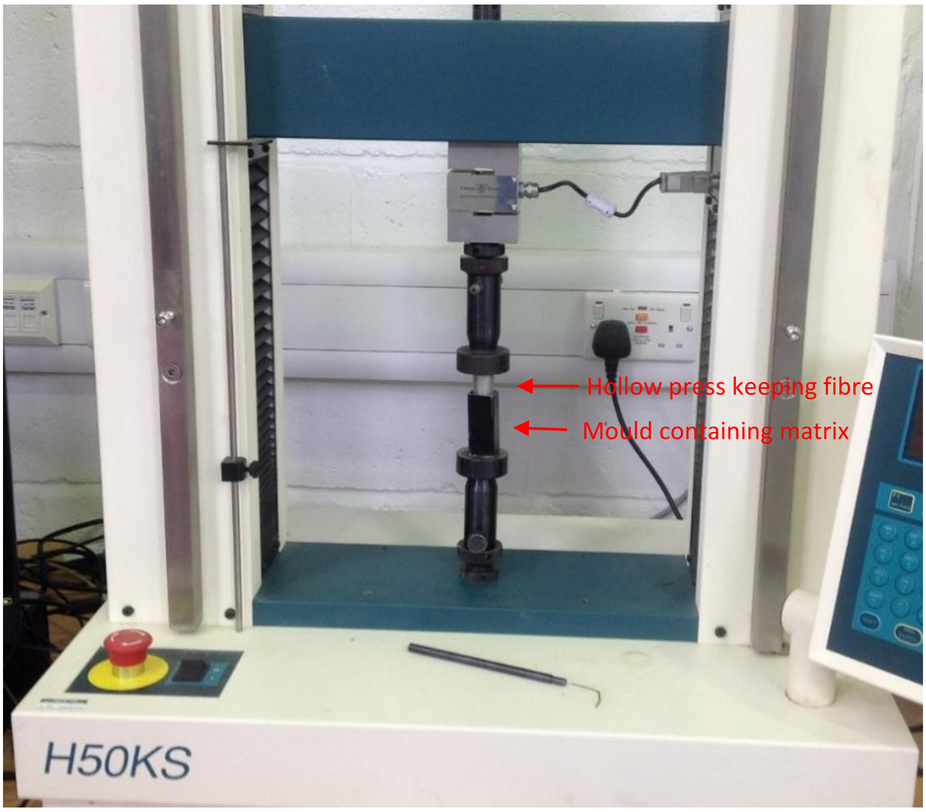


Figure 9.3: Pressing specimen for pull-out test

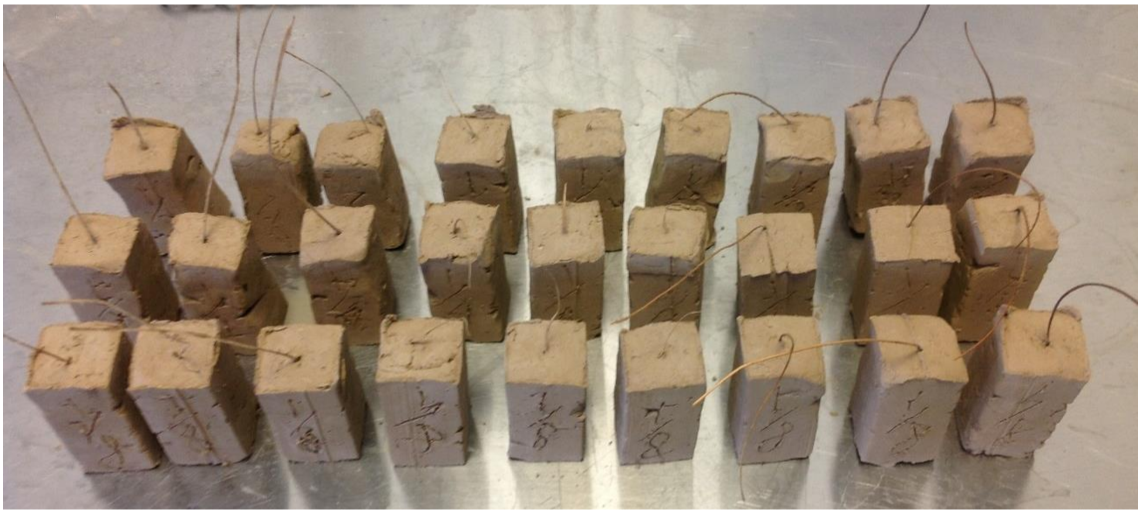


Figure 9.4: Drying samples for pull-out test

9.2.3 Testing methods

9.2.3.1 Fibre distribution in soil matrix

A computerised tomography (CT) scan analysis was conducted to investigate the distribution of the fibres in the soil matrix. A Metric XT H 225 Microfocus CT Scanner was used to scan the cylinder specimens (Figure 9.5). The CT scan produced images (slices) which were modelled with VGStudio MAX version 2.0 to produce a 3D and 2D results of the cylinder specimen showing the orientation of the fibres.

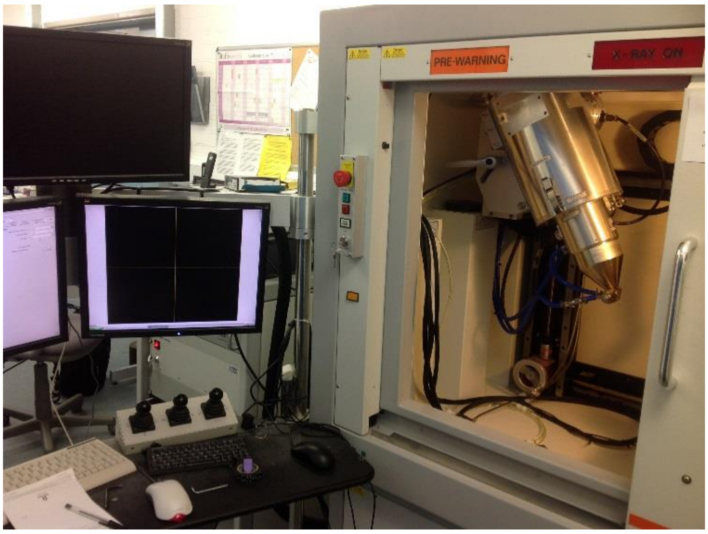


Figure 9.5: Scanning specimen with Metric XT H 225 Microfocus CT Scanner

9.2.3.2 SEM and optical microscope analysis

Scanning electron microscopy (SEM) and optical microscope analysis were conducted to determine whether gaps exist at the peripheral of the fibres in the specimen. Selected cubes from each fibre type were broken to expose the internal parts for the analysis with JSM-6100 scanning microscope and computerised optical microscope (OLYMPUS BX40) with Leica Application Suite version 3.4.0 (Figure 9.6). Each specimen was placed in the JSM-6100 scanning microscope at 100x magnification to determine the gaps at the peripheral of the fibres in the soil matrix. The specimen was also placed in the optical microscope and extra lighting provided to allow the details to be seen clearly on the screen of the attached computer. With the help of the Leica Application Suite installed on the computer, the gaps were measured and recorded.

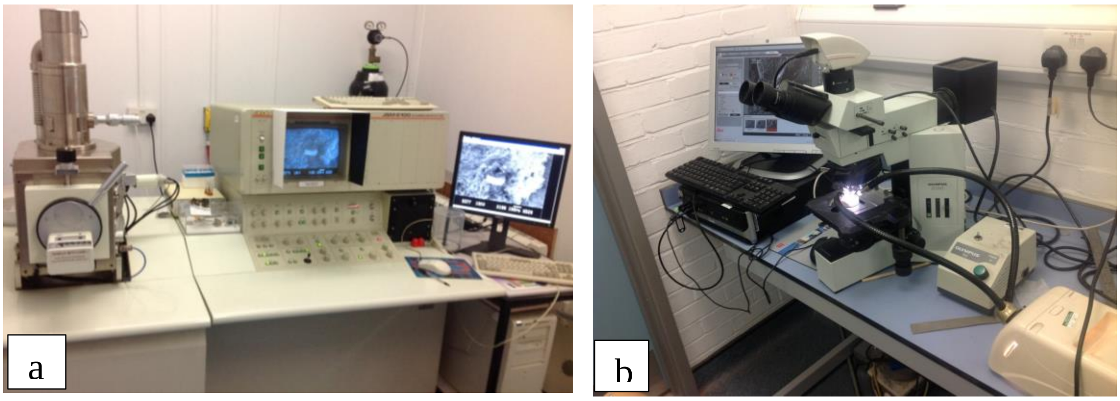
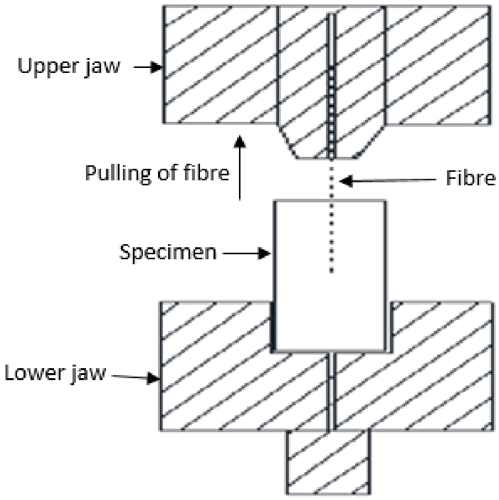


Figure 9.6: Analysing specimens for gaps
(a) JSM-6100 Scanning Microscope, (b) OLYMPUS BX40 Computerised Optical Microscope

9.2.3.3 Pull-out test

The pull-out test was conducted mainly to find out if the fibres in the soil matrix pull-out or fail/break when load is applied on the reinforced soil blocks, and also to determine the interfacial peak strength (IPS) of the fibre-soil composite at the critical fibre pulled-out. A single-fibre pull-out test was carried out following the method used in previous studies on steel fibres in cement composite (Beglarigale and Yazıcı, 2015, Tuyan and Yazıcı, 2012). The specimens were subjected to pull-out using a Tinius Olsen H50KS as shown in Figure 9.7. The pull-out test specimen was fixed to the bottom jaw of the test machine while the free end of the fibre was held by the upper jaw. The matrix remained rigid while, the fibre-held upper jaw moved upward with a rate of 1 mm/min until fibre failed or pulled-out. The interfacial peak strength (IPS) were calculated on the fibres that pulled out and also on the fibres at the minimum length that ruptured (thus 2 lengths).



Schematic diagram

Laboratory photo

Figure 9.7: Pull-out test setup

Equation 9.1 from Subrianto et al. (2015) is usually used for calculating the interfacial shear stress (IFSS) of fibre-matrix material.

$$IFSS = \frac{F_{bond}}{\pi\, t\, D_f} \qquad (9.1)$$

Where: F_{bond} is the first maximum force (N), D_f is the mean fibre diameter (mm) in specimen, and *t* is the matrix thickness (mm) for the IFSS equation. Subrianto et al. (2015) had the fibres through the whole thickness of the specimen, which means the *t* is also the length of the fibres in the matrix.

However, the first maximum force (F_{bond}) was not measured because the initial idea of the pull out test was to determine if the fibres pull out or break in the soil matrix when force is applied. Later, it was realised that the tensile (breaking) strength of the fibres as shown in Table 5.3, the maximum fibre length that pulled out and the minimum length that ruptured as also presented in Table 9.3, and taking the matrix thickness (*t*) as the length of fibre embedded in the matrix at the point of rupture (l_r), it was possible to determine a window for the value of the IPS.

Because the first maximum force was not measured, it was taken as the breaking strength multiplied by the cross sectional area of the fibres embedded in the soil matrix at rupture, which resulted in amended equation (Equation 9.2) which was used for calculating the IPS.

$$IPS = \frac{\sigma_{uts}\,\pi\, D_f^{\;2}}{4\pi\, l_r\, D_f} = \frac{\sigma_{uts}}{4}\frac{D_f}{l_r} \qquad (9.2)$$

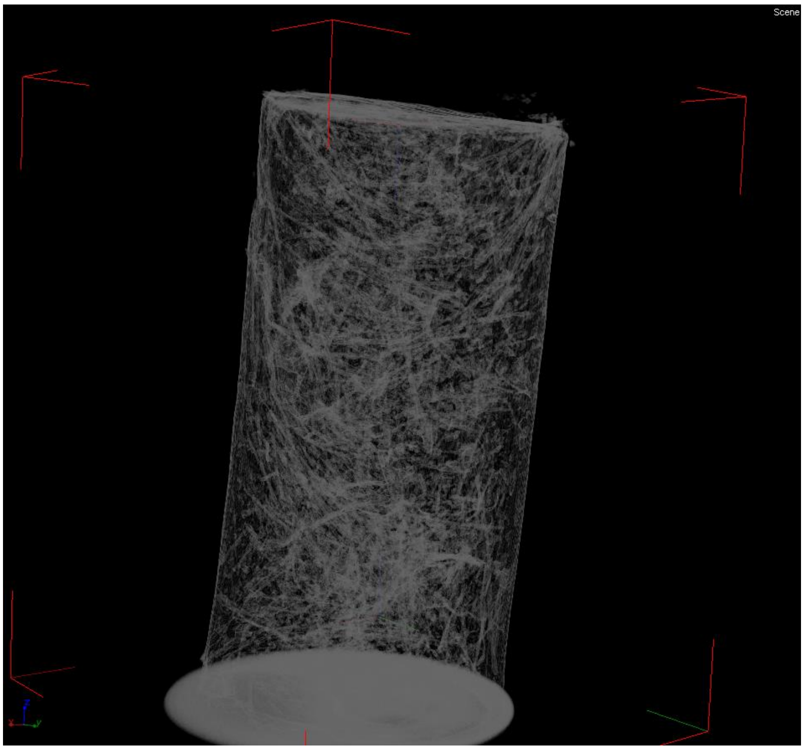
Where: σ_{uts} is the breaking strength multiplied by the cross sectional area of the fibre, (l_r) is the length of fibre embedded in the matrix at the point of rupture.

9.3 RESULTS AND DISCUSSION

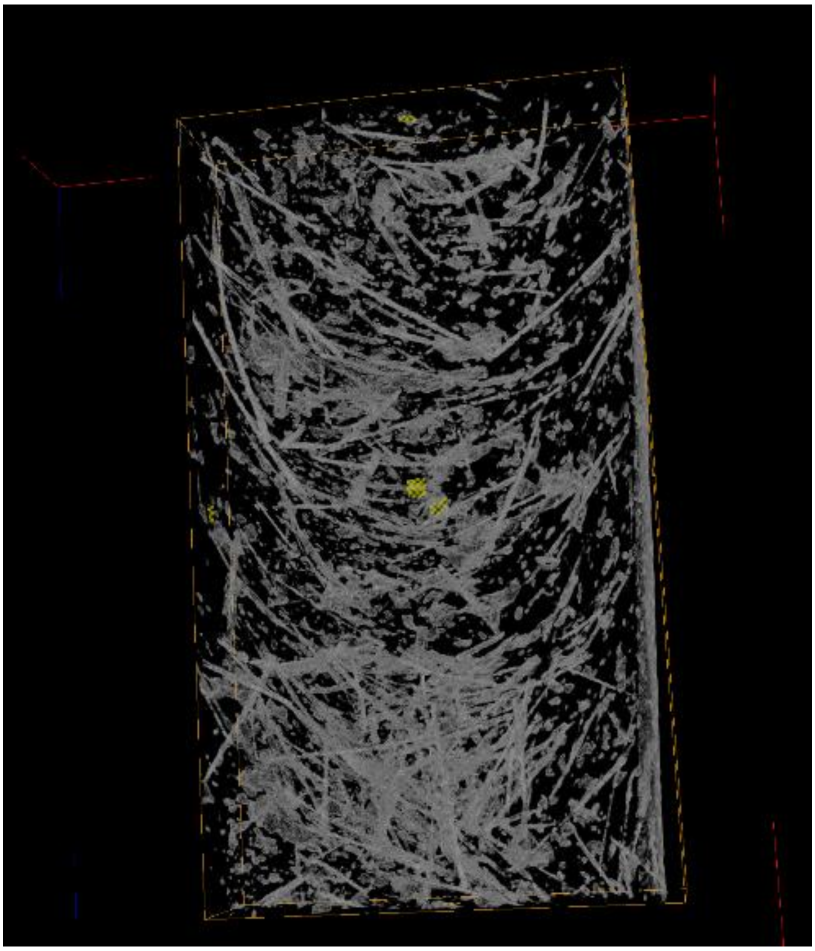
9.3.1 Fibre distribution in soil matrix

There was difficulty in obtaining images showing the fibres in the soil matrix with the CT scanner. This was due to the lower density of fibres as compare to the density of the soil matrix, which resulted in the soil images showing without the fibres. So several trials were done with adjustment of resolution and sample size until one specimen containing coconut fibres of length 25 mm provided this result. The result obtained from the CT scan and modelling of the slices is shown in Figure 9.8. The image obtained shows the cylindrical specimen with the fibres distributed in it. Although the fibres seem concentrated at the internal of the matrix than the peripheral (which is due to the cylindrical shape of the specimen), the fibres are more randomly distributed. This implies that the fibres in the soil matrix are generally well distributed. This agrees well with Diambra et al. (2013) who observed that the use of flexible fibres are usually randomly distributed throughout the soil mass when fibres are used in geotechnical applications.

Studies by Ibraim et al. (2006) and Maeda and Ibraim (2008) found that randomly distributed flexible fibres generate a bond within the soil. This means the orientation of the fibres in the soil matrix have effect on the performance properties of the soil blocks. In the studies of fibre reinforced cement, Maalej et al. (1995) and Slosarczyk (2012) found that the use of randomly distributed fibres in a brittle matrix increase toughness, increase tensile strength, reduce shrinkage and provide good crack-width control.



Full 3D view



Sliced internal 2D view

Figure 9.8: Images from modelled CT scan slices

The grey curved lines show the fibres in the matrix

9.3.2 Gaps between fibre and soil matrix

The images obtained from SEM analysis (with small broken samples) are shown in Figure 9.9. It illustrates the inter-spatial relationship between fibres and the soil matrix of the enhanced soil blocks. Critical observations of the images show that there are gaps formed between the fibres and the soil matrix. Studies by Cao et al. (2006) on biodegradable aliphatic polyester composites reinforced with bagasse, Rivera-Gómez et al. (2014) on wool fibre in the soil and Zhu et al. (2013) on flax/epoxy composites obtained similar results. The extent of these gaps may also be attributed to the disturbances during breakage of the specimen. The gaps recorded were statistically computed to determine the mean and standard deviation values out of the twenty measurements taken from each fibre type. Details of the measurement can be found in Appendix J

The results obtained are presented in Table 9.2 and the images in Figure 9.10. The results indicate that gaps found between coconut fibres and the soil matrix were bigger than those between bagasse and oil palm fibre reinforced blocks. The average gap out of twenty fibre-soil specimens of each fibre type measured show that the gap between oil palm fibres-soil matrix is about half that of coconut fibres-soil matrix, and the gap between bagasse-soil matrix is also about half that of oil palm fibres-soil matrix. The bagasse fibres recorded the smallest gaps with the soil, which implies there is a lower shrinkage of the fibre as supported by lower shrinkage of the bagasse fibre than the others in Table 9.2.

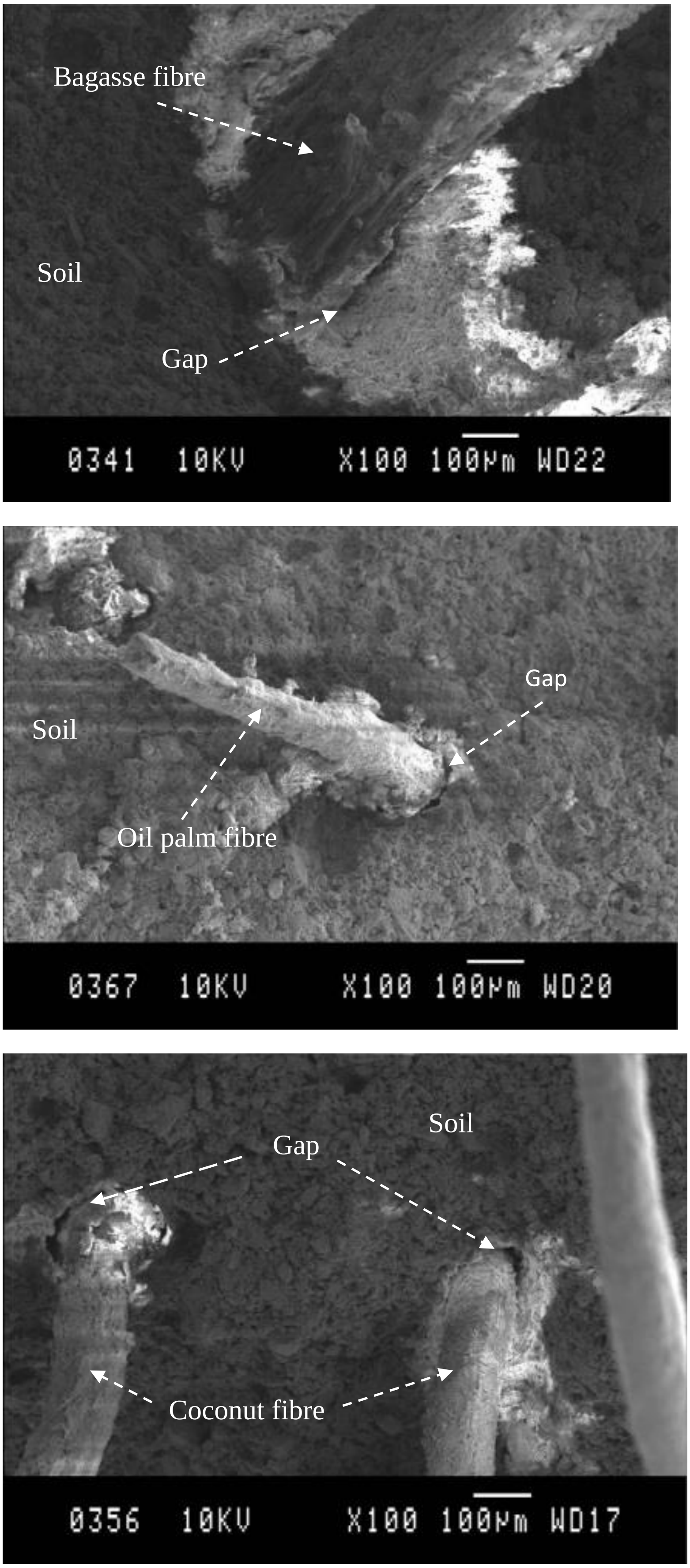


Figure 9.9: SEM micrographs showing gaps between fibre and soil matrix

To determine whether these gaps were caused by shrinking of the fibres or the soil matrix, twenty fibres from each fibre type were randomly selected and measured in dried state and wet state after immersing in water for 48 hrs. Details of the results obtained can be found in Appendix K, and the summary in Table 9.2. The result shows that there were differences between the dry fibres diameter and the wet fibres diameter, with the wet fibres obtaining increase diameter. This suggests the gaps found between the fibres and the soil matrix may be caused by shrinking of the fibres from wet state to dry state. The differences in the diameter of the dry and wet fibres were found to be more than the gaps measured between fibre-soil matrixes, implying some shrinkage take place with the inclusion of fibres in soil.

Table 9.2: Gaps in fibre-soil matrix and difference b/t dry and wet fibre diameters

Difference	**Fibre diameter (mm)**		
	Bagasse	**Coconut**	**Oil palm**
	Mean ± SD	**Mean ± SD**	**Mean ± SD**
Gap b/t fibre and soil matrix (mm)	0.018 ± 0.009	0.077 ± 0.022	0.038 ± 0.006
Saturated fibre diameter (mm)	0.794 ± 0.209	0.623 ± 0.227	0.403 ± 0.132
Dry fibre diameter (mm)	0.769 ± 0.204	0.529 ± 0.211	0.352 ± 0.128
Shrinkage (dry – saturated fibre diameter (mm))	0.025 ± 0.009	0.094 ± 0.023	0.051 ± 0.007
Ratio of gap to shrinkage	0.720	0.819	0.745

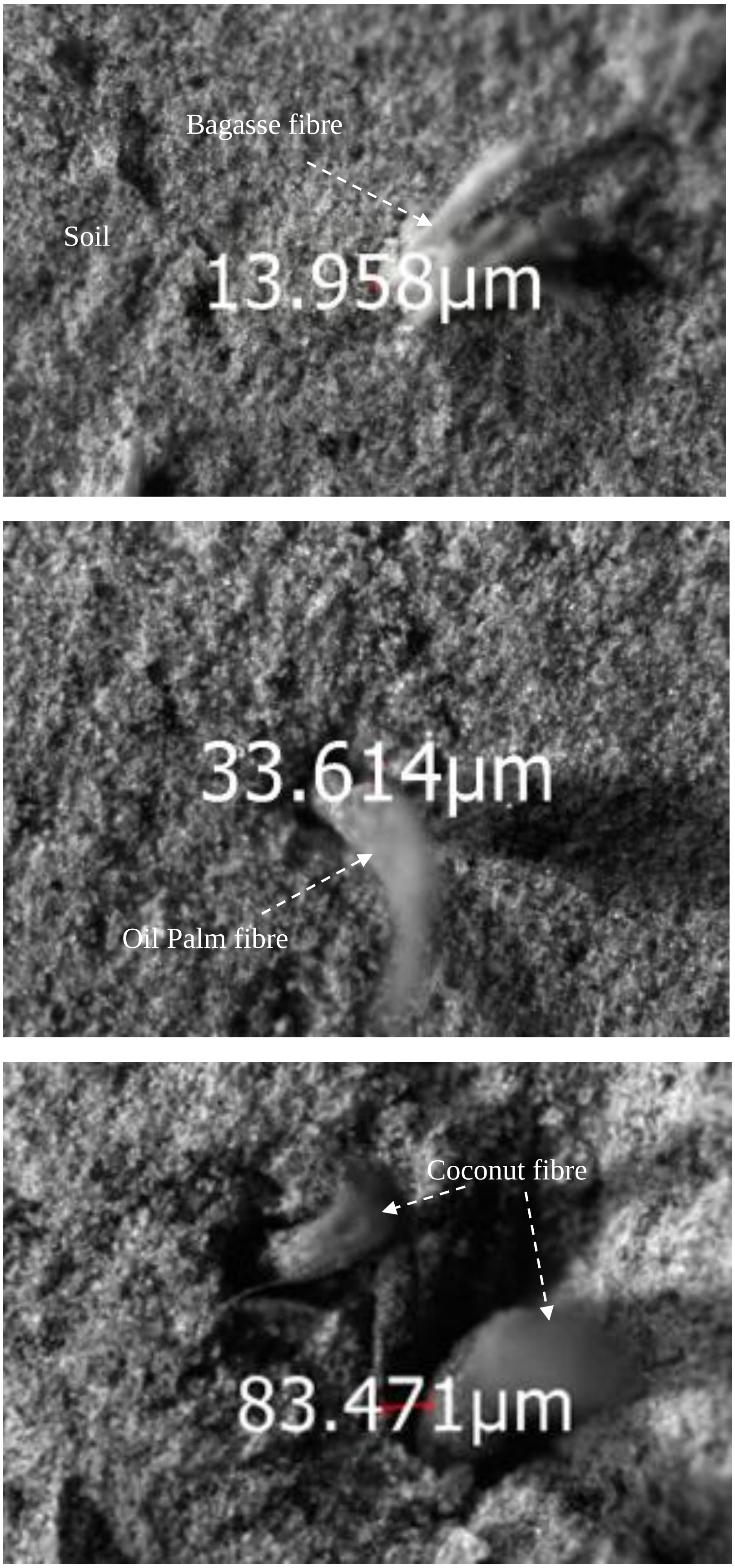


Figure 9.10: Optical microscope micrographs showing gaps between fibres and soil

This could be explained that, when the fibres are kept in water, they absorb moisture and therefore expand and when mixed with soil and compacted the fibres undergo shrinkage due to the compaction pressure, and further shrink when the blocks are dried to their natural stable moisture content. This means that there are two stages that the fibres shrink; (1) shrinkage due to the compaction force when making the blocks, and (2) shrinkage due to drying of the blocks. Meaning the gaps found in the optical microscope analysis represent the gaps created by the drying of the blocks (second shrinkage). It must be noted that these two shrinkage stages are all caused by loss of absorbed water in the fibres, which is the difference in dry and wet fibre diameter. Implying that the fibres expand when kept in water and shrink to its natural diameter through compaction and drying of the blocks.

The fibre-soil matrix is generally affected by the dimensional changes of the fibres which can occur due to changes in moisture and temperature (Ghavami et al., 1999). The changes in fibre dimension occur during the drying of the fibre-soil matrix which may result in a poor interfacial bond (Hejazi et al., 2012). This behaviour of the fibres in the soil can weaken the bond between the fibres and the soil matrix (Ghavami et al., 1999, Hejazi et al., 2012). If the gap between the composites are large, it contributes to pull out effect of the fibres from the matrix which results in adhesion failure (Luz et al., 2007). To determine if indeed the gaps contribute to pull out effect on the fibre reinforced soil matrix, a pull out test was conducted and the results are presented in the next section.

9.3.3 Pull-out result

The pull-out test results obtained are reported in Table 9.3 which indicate that the fibres break or pull-out depending on the length of fibre embedment in the soil. It can be seen that all the three replicates of bagasse fibre-soil specimens pulled out at fibre lengths 7 mm embedded in the soil matrix, while oil palm pulled out at 3 mm length. With coconut fibres, two out of three replicates for 13 mm and all the three replicates for 6 mm pulled out of the soil matrix.

Table 9.3: Pull-out test results of fibre-soil composite
(Fraction indicates fibres pulled out over test replicates)

Fibre	Length of fibre embedded in soil matrix (mm)											
	55	28	14	7	52	26	13	6	19	10	5	3
Bagasse	0/3	0/3	0/3	3/3								
Coconut					0/3	0/3	2/3	3/3				
Oil Palm									0/3	0/3	0/3	3/3

The results show that the fibres pulled out with less lengths embedment in the soil, whereas the fibres failed with increase lengths embedment in the soil. Some of the fibres failure can be seen in Figure 9.11. It therefore means the critical pull-out of fibre lengths is between the smallest length where the fibre ruptures and the next length where it pulls out, thus 7 - 14, 3 - 5 and 13 - 26 mm respectively for bagasse, oil palm and coconut fibres. The highest fibre (coconut) length pull-out can be attributed to the highest tensile strength of the fibre as shown in Section 5.5.4.

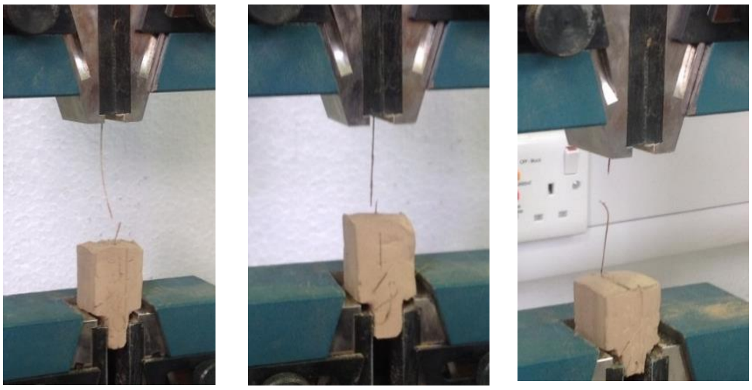


Figure 9.11: Fibres failure under pull-out test

In addition, the compressive strength of the coconut fibre reinforced soil blocks performed better than the bagasse and oil palm fibres reinforced blocks in Section 8.4.2. The pull out for all the fibre lengths can be explained by fibres poor interfacial bond with the soil matrix and short lengths of the fibres implant in the soil matrix. The results means that with natural fibres in soil, the mechanism can either be pull-out *or* rupture of the fibres, whereas studies (Beglarigale and Yazıcı, 2015, Tuyan and Yazıcı, 2012) on steel fibres in cement composite the mechanism is *always* pull-out because steel fibres are *designed* that way. If they were long enough they would rupture.

The results of the interfacial peak strength between the soil matrix and the fibres pull-out are presented in Table 9.4. The table shows IPS of the fibres at the maximum length of fibre embedment and also the minimum length of fibre embedment. The minimum diameter represents the lowest IPS and the maximum diameter, the largest IPS. The mean diameter values are included because there is some uncertainty due to the method used. The outside columns are due to the uncertainty about fibre diameter (see Section 5.5.1).

The results show increase IPS with increased fibre diameter of all the fibre types. Due to different lengths of fibres embedded in the soil matrix, the exact point of fibre pull-out was not identified, and therefore assumed that the pull-out was between minimum length and the preceding failure fibre lengths as shown in Table 9.3.

Table 9.4: Interfacial peak stress

	Maximum length		**Minimum length**	
	Min diameter	**Mean diameter**		**Max diameter**
Bagasse	0.14	0.59	1.17	2.64
Oil palm	0.24	0.85	1.83	4.82
Coconut	0.75	3.08	5.13	18.69

Note: the experiment results in an uncertainty of 100% as interfacial failure occurs between two values, however variations in fibre properties result in a much larger uncertainty.

The IPS values obtained in the this study are higher than those obtained by Tang et al. (2010) who used polypropylene fibres in matrix, and Subrianto et al. (2015) who use coir fibres in matrix. This can be attributed to the compaction pressure applied on the specimen, while this study applied 10 MPa, Subrianto et al. (2015) used only 0.5 to 1 MPa pressure. Another contributing factor may be the fibres diameter, as this study used fibres with mean diameters from 0.38 to 0.78 mm, Tang et al. (2010) and Subrianto et al. (2015) used fibres with mean diameters 0.048 and 0.298 mm, respectively. This is supported by the results which shows increase IPS with increased diameter of all the fibre types from minimum to maximum.

9.4 SUMMARY

This study investigated the internal mechanism of soil matrix reinforced with coconut husk fibres, oil palm nut fruit fibres and sugarcane bagasse fibres. The main conclusion of the investigation can be found in Section 12.2. On the basis of the experimental results obtained, the following conclusions can be drawn:

- CT scan micrograph revealed that the fibres in the soil matrix are more randomly distributed. This implies that the fibres in the matrix have unsystematic orientation as compared to steel in reinforced concrete. This is however good to reduce cracking effect and also increase strength.

- SEM and optical microscope analysis found that gaps exist between the fibres and the soil matrix. Coconut fibres-soil matrix recorded the biggest gap while bagasse obtained the least gap between the fibres and the soil matrix.
- The study also found that the fibres in the soil matrix undergo changes in size (diameter). The fibres expand when wet (during the production of the fibre enhanced soil matrix) and return to their natural state when dried. This accounts for the gaps that are created in the fibre reinforced soil matrix.
- Natural fibres in soil matrix can either be pull-out or break under failure force. This is contrarily to steel fibres in cement composite which always pull-out. The interfacial peak strength of the soil matrix and the fibres' pull-out increased with increase fibre diameter. Further work is required to establish the exact point of fibres pull-out, as the pull-out was between two fibre lengths.

CHAPTER 10

10 OVERVIEW DISCUSSION

10.1 INTRODUCTION

The work contributes to knowledge by the use of fibres for reinforcement of novel building soils blocks, using three different agricultural waste fibres in two different soil types. The study investigated the properties and internal mechanism of the fibre enhanced soil blocks. The experimental work, results and discussions have been presented in Part III of this thesis. This section of the work provides explanation of the theory behind the observations made and connections between different observations.

10.2 PHYSICAL PROPERTIES OF THE FIBRE REINFORCED BLOCKS

It was observed in Section 8.3.1 that the rate of water absorption in the fibre enhanced soil blocks were higher that the unreinforced soil blocks, which is a common trend observed in previous studies (Bahar et al., 2004, Ismail and Yaacob, 2011). This increase can be connected with the high water absorption of the fibres as observed in Section 5.5.3, when the fibres water uptake was as much as 103%, 209% and 219%, respectively for oil palm, coconut and bagasse fibres. The fibres absorb water due to the cellulose properties which create a pathway through the material (Ghavami et al., 1999, Jeefferie, 2011). Furthermore, the gaps observed in Section 9.3.2 between the fibres and the soil matrix may contribute to the sorption rate of the fibre enhanced soil blocks.

It was also observed in the linear shrinkage test results that there was decreased shrinkage with increase fibre addition to the blocks. Soil B blocks outperformed the soil R blocks in the resistance against shrinkage, which can be linked to the lower plasticity index of soil B. It was observed in Section 4.5.4 that plasticity index of soil B was 13.9% while soil R was 23.9%. A study by Walker (1995) found that soil with a plasticity index of <20 will have lower shrinkage as compared to a plasticity index >20. This means the rate of reduction in the drying shrinkage does not depend only on the fibres, but also the properties of the soil.

10.3 MECHANICAL PROPERTIES OF THE FIBRE REINFORCED BLOCKS

As observed in Section 8.3.2, the compressive and tensile strengths of the fibre reinforced blocks increased with fibre addition until 0.25/0.5 wt% and then decreased. This provided an optimum strength of the blocks. This is frequently found result in soil blocks reinforced with natural fibres (Akbulut et al., 2007, Bouhicha et al., 2005). The increase result is due to the fact that fibre inclusion in the soil blocks prevent crack propagation (Millogo et al., 2015) and friction between the fibre and the soil matrix. The compressive strength increase of between 39% and 42% and tensile strength of between 16% and 38% at the optimum is sufficient for a low-rise building, which is in agreement with Millogo et al. (2015). The decrease in strength with the addition of further fibre content to the soil could be explained by the fibres distribution in the soil as shown in Figure 9.8, which the fibres knock and overlap each other (Medjo Eko et al., 2012). This results in reduced cohesion between the fibres and the soil causing the soil to weaken (Millogo et al., 2014). Another possible cause of the decrease in strength is the increase void content in the blocks. It was observed in Figure 9.9 that gaps are formed between the fibres and the soil matrix, which implies increase fibre content will lead to increased gaps/voids content in the blocks. Morel and Gourc (1997) observed that increased voids content in soil matrix weakens the strength.

Another observation made was that the failure of the fibre reinforced soil blocks was more gradual and with multiple cracks (this agrees with previous observations (Bouhicha et al., 2005, Cai et al., 2006)), and the splitting block parts were held together by the fibres. This can be linked with the pull-out test result at Section 9.3.3, which the fibres fail or pull-out in the soil matrix under force. This means that when the soil matrix fails, the fibres would have not reached their breaking point, and because of longer length embedment in the soil, they will keep holding the broken matrix parts together. It therefore means that, though gaps were found between the fibres and the soil matrix in Figure 9.9, they are not that large to allow for easy pull-out of the fibres from the soil matrix at longer length embedment. It was however, observed that fibres with short length embedment at the failure regions of the soil matrix pulled out.

10.4 DURABILITY PROPERTIES OF FIBRE ENHANCED SOIL BLOCKS

In both wearing and erosion test results, it was observed that the rate of depreciation of the material decreased with increase fibre content. There was between 20% and 50% reduction in wearing and 44% and 70% in erosion. This implies the fibre inclusion in the soil increased the resistance of the block, making the blocks more durable. It was observed during the tests that the fibres in the blocks shielded the soil particle from been washed away or blown out which increased the durability of the blocks. This could be linked to the phenomenon of tree roots protecting earth from erosion by holding the earth within its boundary as explained by Huat and Kazemian (2010) and Michalowski and Zhao (1996). This could be linked to the observation made in Figure 8.18, where the splitting block parts were held together by the fibres. This implies the fibres in the soil protect the soil from being shed away. It must be noted that from Section 5.5.2, the fibres have different specific weight (density), implying that the total number of fibres in the blocks with different fibre types will differ due to the replacement of mass (weight) contents. This means the fibres with less density are likely to have greater number of fibres in their blocks which might be advantageous for protection of the blocks against erosion and wearing. However the results from Section 8.3.3 shows that there is little change in erosion and wearing after 0.5 wt% of fibre inclusion.

In both wearing and erosion, soil R blocks outperformed soil B blocks. Similar observation was also made with compressive and tensile strength of the blocks. This may be primarily attributed to the higher clay content of soil R, which improves bonding between fibres and the matrix. From Section 4.5.2, the particle size distribution results showed that soil R contained 30% clay while soil B had 12% clay content. Furthermore, the Atterberg limit results in Section 4.5.4 indicate that soils B is low plasticity clay (CL) while soil R is high plasticity clay (CH) soil (British Standard Institute BS 5930, 2015). Contrary to the general criteria for soil suitability which have been developed for binder stabilised blocks (Houben and Guillaud, 1994), which recommends low clay soil for use, high clay soil was found to be suitable for the fibre reinforced blocks.

10.5 RELATIONSHIP BETWEEN THE PROPERTIES

In Figure 8.19, it was observed that compressive and tensile strengths poorly correlated for each fibre and soil type (0.249 > r > 0.720) although compressive and tensile strengths increased together. This indicates that while generally a block that is strong in compression will also be strong in tension, compressive testing is a poor predictor of tensile strength. This contradicts findings of other studies such as Walker (2004) which reports better correlations of tensile and compressive strengths of binder stabilised soil blocks.

A number of studies (Venkatarama Reddy and Jagadish, 1995, Walker, 2004) have suggested that physical or mechanical properties may be used as proxy measures for durability for binder stabilised blocks. Observation made in Table 8.3, shows that mechanical properties are very poorly correlated to mechanical properties with both positive and negative relations ($-0.280 < r < 0.428$) and differences between the tests not significant ($0.059 < p < 0.870$). This is in contrast with recommendations for binder stabilised blocks. The reason for this difference might be that, for binder stabilised blocks, both mechanical and durability properties increased with increase binder content, whereas for fibre reinforced blocks the properties increased with increase fibre content to an optimum and have to decrease or level off.

Furthermore, it was observed in Table 8.4, that water absorption negatively correlated with erosion ($-0.845 < r < -0.943$). This means that, although the blocks may allow greater water ingress which may be problematic for damp condition, however the ingress does not correlate with increased erosion as would normally be assumed. It was observed during the experiment that, though the fibres absorb water (that is water transport through it), it does not easily wash away during erosion because of longer length embedment in the soil. This means the water can have access to the fibres (and possible absorb some water), but the fibres will still be held in the blocks without being washed away and also shield the soil particles from being washed away so easily, which reduce the rate of erosion.

10.6 SUMMARY

This section of the work provided explanations to the observations and connections between different observations made in this study. From the discussions, the following concluding summary can be made:

- Physical properties of the blocks are generally affected by the soil properties as well as the fibre properties. For example fibres high water absorption contributed to the high sorption of the fibre reinforced blocks, and also the lower plasticity index of the soil also contributed to lower dry shrinkage of soil B.
- The mechanical performance of the blocks were affected by the fibre distribution and gaps observed in the fibre reinforced soil blocks. It was discussed that overlapping fibres as well as increase fibre content which is associated with increase void content contributed to the reduction of the strength of the block after obtaining an optimum strength.
- The increased wearing and erosion performance of the blocks were linked to the theory of tree roots protecting earth from erosion by holding the earth within its boundary as explained. In both wearing and erosion, soil R blocks outperformed soil B blocks which is associated with the high clay content in soil R, contrary to soil suitability criteria for binder stabilised soil blocks.
- It was also observed that mechanical properties correlated poorly with physical and durability properties, which is in contrast with recommendations for binder stabilised blocks.

PART IV

IMPACT DISSEMINATION

CHAPTER 11

11 IMPACT DISSEMINATION ASSESSMENT

11.1 INTRODUCTION

This chapter of the research project consider the impact of the work beyond its' immediate academic environment. Its' influence is planned to extend beyond academic to the local communities (both rural masons and clients) living in the rural Ghana where earthen construction is common. The chapter considers who will benefit and how, the construction industry in Ghana, the informal construction sector in Ghana, strategies for maximising impact, and evaluation of workshop training followed by summary of the chapter.

11.2 BENEFITS AND BENEFICIARIES

The direct beneficiaries of this research include the earth construction users, governments of LED countries and real estate developers, academic community (researchers, educationalists and students) and builders. The potential beneficiary groups and the major benefits of the research can be found in Table 11.1. There is an increasing demand of shelter for most LED countries as people sleep at night in kiosks, open spaces and growing slum settlement.

Government and real estate developers can play a significant role in creating and adopting soil enhancement techniques in order to provide houses with locally available and abundant materials at low-cost for it dwellers. In the light of this, the findings of the study will help government and real estate developers to have alternatives to the conventional building materials which will be within their means to provide. Governments can be in a better position to formulate policies on the use and adoption of enhance soil blocks for building houses. The findings of the study will assist government and real estate developers in producing low-cost building materials to produce more houses, especially to the poor in order to reduce the housing deficit rate in their countries considerably.

Table 11.1: Matrix of potential beneficiary groups

Benefits	**Beneficiary groups**					
	AC	GLED	CI	ECU	RED	BEH
Cost saving		✓	✓	✓	✓	
Energy conservation		✓	✓	✓	✓	✓
Environmental protection	✓	✓	✓	✓	✓	✓
Access to extension of technology		✓	✓	✓	✓	✓
Information to support decision-making	✓	✓	✓	✓	✓	✓
Information to support policy decision		✓	✓		✓	
Knowledge to select new avenue of research	✓	✓	✓		✓	
Reduced social exclusion		✓	✓	✓	✓	✓
Improve citizens' quality of life	✓	✓		✓		
Reduction of housing deficits	✓	✓	✓	✓	✓	
Provision of decent housing	✓	✓	✓	✓	✓	✓

AC - academic community; GLED - governments of less economic developed countries; CI – construction industry; ECU - earthen construction users; RED – real estate developers; BEH – builders of earthen houses

Researchers, educationalists and students in the construction area will also find the study useful in their profession or study by using it as a reference and guide in the area of soil stabilisation by enhancement and specifically in the use of agricultural waste as enhancement of soil blocks. The outcome of the study will also contribute to the field of knowledge in sustainable construction where building materials are obtained with less impact on the environment and less consumption of energy. The study makes this possible because it will do away with the use of cement which requires high energy for production, and also contribute to environmental pollution. It will also encourage other researchers to identify other agricultural and industrial wastes that can be used as enhancement of soil blocks to promote the technology in the construction industry. Future researchers can also utilise the outcome of the study to research into other dimensions of building materials for producing low cost housing, as well as the environmental friendly materials.

The earth construction users (usually those in the low-income bracket), especially those who want to acquire their own house, the outcome of this study is of great benefit to them. This is due to the fact that it will help them to use locally available and abundant material for constructing their houses, which will prevent high cost of acquiring conventional materials and transportation cost, by so doing acquiring their own houses within their economic means through self-help and/or contracting of builders. This has the potential of reducing housing deficits and the number of slum dwellers, especially in the urban areas.

Builders such as contractors, engineers and masons will find this study relevant in terms of appropriate techniques and processes involved in making soil enhanced blocks with agricultural waste. The study also provides guidance on preparing the raw materials for making the blocks and also give the procedure in preparing the block. The study also provides information on the mix ratio of the raw materials that will provide the optimum strength of the soil enhanced blocks so that builders can adopt it in the design and construction of low cost houses.

11.3 THE CONSTRUCTION INDUSTRY IN GHANA

11.3.1 Background

Construction is one of the important industries in the social-economic development of any country. The construction industry provides infrastructural development, creates employment and provides security to people and their property. The infrastructure includes schools, hospitals, houses, offices, sewerage, roads, ports and power and telecommunication systems (Osei, 2013). The construction sector in Ghana has expanded rapidly in the past two decades, with about 10% growth per annum making it the second largest contributor to the national Gross Domestic Product (GDP) (Ghana Statistical Service, 2014). The government is the major developer in the construction industry providing roads, water and public structure. However, private developers and individuals dominate residential housing provision. Ghana has abundant resources, such as raw materials (especially timber, sand, stone/gravel and lime) with abundant of inexpensive and trained labour. Traditional and local materials such as earth/soil, bamboo and natural fibres are abundant and available in almost every part of the country.

Notwithstanding, the construction industry in Ghana is faced with many challenges. The 2010 Population and Housing Census revealed that there is pressure on the existing housing infrastructure as the population density of the country increased from 79 per square kilometre in 2000 to 103 per square kilometre in 2010. According to the Ministry of Works and Housing, the housing deficit in Ghana is about 1.5 million units 1 (AGI, 2013). There is therefore, enormous demand for housing in Ghana, but the construction and building industry is incapable to meet the demand due to several challenges. The challenges include lack of government support; low access to capital; difficulty in accessing land; and over reliance on the import of conventional building materials as stated by Sampson Ahi, Deputy Minister of Water Resources, Works and Housing

(Lamudi, 2014). The latter is a major issue which results in increase cost of housing, making it difficult for those in the low-income bracket to afford decent accommodation. The use of locally available materials could be useful in reducing the housing deficit and also help provide decent housing for those in the low-income bracket. According to Osei (2013) the labour cost of the construction sector in Ghana and other developing countries is relatively cheap. This means that the main issue with cost of housing in developing countries is with the cost of the building materials, rather than the high cost of labour.

11.3.2 The informal construction sector in Ghana

The informal construction sector in Ghana, like in many other African countries, is noted for its variety and heterogeneity (Adu-Amankwah, 1999). A study on the informal construction sector in Ghana identified different operations such as (1) manufacturing, (2) construction and (3) services. (Osei-Boateng and Ampratwum, 2011). The main construction trade workers in the informal construction sector in Ghana include masons, steel benders, carpenters, electricians, plumbers and painters. These construction trade workers are male dominated and majority of them dropped out of school and acquired their skills through apprenticeship for number of years. Besides these trade workers, there are different types of manual labour that are provided in the informal construction sector in Ghana. These types of labour as identified by Adu-Amankwah (1999) and Osei-Boateng and Ampratwum (2011) are described below:

1. *Family labour*, is a unique type of rural informal labour where family members provide manual assistance to any work other family members are involved. It is seen in almost all the economic sub-sectors in the rural communities. This type of labor is predominant in the construction, fishing and farming sectors. In some rural communities, this type of labour is crucial for the survival of the construction sector. It is also used as an apprenticeship for transfer of skills from the older generation to the new generation.
2. *Child labour*, is somehow similar to the family labour. With this type of labour, parents or close family members use children especially those who have never been to school or school dropped out to assist them in their occupations. This is common in the construction and other sectors especially in the rural areas. Students are also not left out, they are engaged mostly during the weekend and vacation periods.

3. *Casual labour*, which is also known as "by-day" by the locals is a type of labour work which the workers are paid at the end of the day's work, hence the name by-day. In the construction sector, number of these unskilled works are engaged based on the demand of the day's work. Casual workers are often engaged on making of blocks, excavation of trenches, mixing and carrying of materials on site.
4. *Apprenticeship,* in the local form is when young men and women undertake informal training to primarily acquire skills in the informal sector. During the training, the apprentice provide labour work for their masters which are usually not paid, but as a service to their master. The apprentice provide labour work for their master at construction site through which they learn the trade skills. The apprenticeship usually take between two and four years depending on the type of trade.
5. *Communal labour*, is a type of labour where people in a community come together to assist in projects for the community or assist each other in turns. Communal labour is common in the sectors that are popular in the rural areas such as construction, farming and mining. In the construction sector, communal labour is used to support construction of school buildings, public toilet facilities, chief palace and individual's residential houses. It is also used to clear public pathways and roads sides in the rural areas.

All these labour types provide manual workforce for the rural construction. They are engaged by master builders (masons, carpenters, painters, plumbers and electricians) to undertake the menial (unskilled) works on site. The masters are usually those who have completed technical and vocational training and sometime have undergone apprenticeship training after which they have worked and acquire experience for many years.

11.4 STRATEGIES FOR MAXIMISING IMPACT

Engagement of the beneficiary groups was achieved and impact maximised through both academic and non-academic approaches. The methodology used in the study and the results obtained from the study are being published in high-impact peer-reviewed journals (such as *Building Research and Information* and *Construction and Building Materials*). International conferences such as *First International Conference on Bio-Based Building*

Materials 2015 in France were also used to disseminate the study outcome to the academic community. The research thesis and other outputs will be made available for free download from the University of Portsmouth repository website.

A technical guide on the production of agricultural waste fibre reinforced soil blocks has been prepared (see Appendix L) and distributed to the following beneficiaries:

- Government agencies such as town engineers at the local assemblies, Building and Road Research Institute (BRR) and parliamentary committee on works and housing.
- Real estate developers such as Ghana Real Estate Development Association (GREDA) and private real estate developers.
- Builders such as building contractors, engineers, architects and masons.
- Earth construction users such as people in earthen housing dominating communities.

Focus group workshop training has been organised for masons in Ghana who are directly involved in supervising and constructing earthen structures. The masons were selected because they are the main people who are involved in producing and using soil blocks for building houses for their clients. Due to the large numbers of masons involved, the master masons were selected as trainer of trainees for the workshop, so that they can learn the techniques of producing the fibre enhanced soil blocks and also go and train other masons. Two workshop training sessions were organised, one for those in Southern Ghana and the other in the Northern Ghana. A snow-ball approach was used to contact and invite the masons for the workshop training. This is because the researcher did not know all the master masons and their locations; so those he was able to identify provided the snow-ball nucleus which spread until majority of the master masons were contacted. The first training was held on 2nd February 2015 at Accra for the Southern sector and the other was held on 6th February 2015 at Kumasi for the Northern sector. Some of the photos of the workshop training are shown in Figure 11.1. Materials provided for the workshop training include:

- Writing pads
- Pens and pencils
- Technical guide on the production of agricultural waste fibre reinforced soil blocks
- Samples of fibre enhanced soil blocks

- Posters on the benefits and production of agricultural waste fibre reinforced soil blocks (see Appendices M and N).

During the workshop, the researcher took the participants through the benefits (economic, environmental, social and technical) of fibre enhanced soil blocks, the process involved in preparing the fibres, preparation of soil, mixing of the materials, moulding of the blocks and drying of the blocks. Participants were allowed to ask questions and answers provided. A feedback form (see Appendix O) was given to the participant to evaluate the workshop training and give suggestions for improvement. Because the participants travelled from far towns and villages to the training centres, their transport fares were paid to them which increased attendance. Breakfast and lunch were also provided as motivation to attend.

Figure 11.1: Photos of workshop training

11.5 EVALUATION OF WORKSHOP TRAINING

11.5.1 Background

In all, one hundred and eleven (111) trainer of trainee masons were contacted and invited to attend the workshop training, 62 from Southern sector and 49 from Northern sector.

Out of these, 49 and 38 attended the workshop training respectively from Southern sector and Northern sector, making a total of 87 attendants. At the end of the training, the feedback form was distributed to all the participants to complete, out of which at total of 81 feedback forms were completed and returned (47 and 34 respectively from Southern and Northern sectors).

The participants of the workshop were given the feedback forms to rate their agreement of disagreement on the usefulness and benefits of the fibre enhanced soil blocks and organisation of the workshop training with a five-point Likert scale. They were also asked to provide suggestions and comments for improvement. The Likert scale used was from strongly disagree (1) to strongly agree (5). Content validity was established by a panel of two expert. Construct validity was also ensured by critically developing the indicators within established theoretical framework. Cronbach alpha reliability tests for the items were above the recommended 0.7 (Straub et al., 2004), with a reliability coefficient of all the 13 items measuring a composite value of 0.73. Therefore the scales could be considered reliable. The computed mean ratings were compared with the theoretical mean rating (assuming normal distribution of responses above neutral) of 3.0, in order to determine the participants agreement to the items. Descriptive analysis of the participants' responses are presented in Table 6.2. The responses are discussed under three main headings: (1) benefits of the fibre enhanced soil blocks, (2) organisation of the workshop, and (3) further suggestions and recommendations from the participants.

11.5.2 Benefits of the fibre enhanced soil blocks

Cost

It can be seen from Table 11.2 that the participants ranked C1 first (1st) with mean / Standard deviation value of 4.40 ± 0.86 which is between agreed and strongly agreed. This shows that '*fibre reinforced soil blocks can be used to produce low-cost houses*' was agreed by the respondents as the highest benefit of the fibre enhanced soil blocks. C2 and C3 are all within the first five ranked items, implying that the cost of the fibre enhanced soil blocks will be affordable for those in the low-income bracket. Some respondents' comments on the research on the enhanced on blocks are quoted below:

> "*The research will help to produce low cost housing and should be introduced in the country*"
>
> "*The raw materials used are cheap and abundant in Ghana*"

Table 11.2: Descriptive statistics: participants' response

Code	Statement	N	Mean	Std Dev	Std. Error	C.I. of Mean	Rank
C1	Fibre reinforced soil blocks can be used to produce low-cost housing	81	4.40	0.86	0.10	0.19	1st
E1	Using fibre reinforced soil blocks will help to produce cool room temperature houses	81	4.37	0.97	0.11	0.21	2nd
U1	I find the fibre reinforced soil blocks useful for building houses	81	4.31	0.68	0.08	0.15	3rd
C2	Resources require for producing fibre reinforced soil blocks are available	81	4.26	0.77	0.09	0.17	4th
C3	Fibre reinforced soil blocks will be affordable	81	4.16	0.93	0.10	0.21	5th
O1	I am satisfied with the general organisation of the workshop	81	4.14	0.77	0.09	0.17	6th
U2	Fibre reinforced soil blocks can be used to address inadequate housing problem	81	4.13	0.90	0.10	0.19	7th
O2	The delivery of the workshop was satisfactory	81	4.13	0.62	0.07	0.14	8th
O3	The resources provided for the workshop were helpful	81	4.11	0.74	0.08	0.16	9th
E2	Using fibre reinforced soil blocks will help to reduce pollution of the environment	81	4.10	0.93	0.10	0.21	10th
U3	Using fibre reinforced soil blocks will help to produce durable houses	81	4.07	0.85	0.10	0.19	11th
U4	I intend to use fibre reinforced soil blocks in future	81	4.00	0.61	0.07	0.14	12th
U5	Producing fibre reinforced soil blocks will be easy	81	3.94	0.84	0.09	0.19	13th

C – Cost; E – Environmental; U – Usefulness; O – Organisation of the workshop

As the cost of construction materials constitutes between 60% and 70% of a building (Danso and Menu, 2013), the reduction of the materials cost will invariably reduce the cost of the entire project. This will make the use of the fibre enhanced soil blocks for building house incurring low-cost due to low-cost of the material (Zami and Lee, 2011). Another important contribution to the low-cost is the production of the blocks at the site where the construction work takes place, as compared to conventional building materials which are imported or manufactured in urban towns and have to be transported to other parts of a country at long distances which makes the materials very expensive and invariably increase the cost of housing (Fernandes et al., 2007).

Environmental

The participants ranked E1 '*using fibre reinforced soil blocks will help produce cool room temperature*' second (2^{nd}) with mean / Standard deviation value of 4.37 ± 0.97 which is also between agreed and strongly agreed. Soil blocks provides a cool room temperature due to its good thermal insulation properties (Arumala and Gondal, 2007, Danso, 2013). E2 *'using fibre reinforced soil blocks will help reduce pollution of the environment'* obtained Mean value of 4.10 which also shows participants' agreement to the item. This is supported by the fact that improper disposal of agricultural waste such as burning can give rise to ammonia and methane emissions that can lead to acidification and contribute GHG (European Environmental Agency, 2006). This means the incorporation of the agricultural waste fibres in blocks will have positive effect on both internal and external parts of housing environment. Furthermore, manufacturing of fibre enhanced soil blocks has little effect on the environment as compare to cement and sandcrete blocks production, which contribute high carbon emission and pollute the environment.

Usefulness

U1 '*I find the fibre reinforced soil blocks useful for building houses*' was ranked third (3^{rd}) by the respondents with mean / Standard deviation value of 4.31 ± 0.68 which is also between agreed and strongly agreed. The respondents therefore consider the fibre enhanced soil blocks to be used to address inadequate housing problem in the society as U2 was rated above 4.0 (agree) scale. The respondents rated U3 and U4 items 4.0 (agree) scale, meaning they find the fibre enhanced soil blocks useful to the society and can be used to produce durable houses. This is important because the main reason for enhancing soil blocks is to improve the engineering properties for better resistance to load and weathering (Minke, 2009). However, U5 '*producing fibre reinforced soil blocks will be easy*' was ranked 13^{th} (the least), which means the respondents find the process of producing the agricultural waste fibres may not that easy. Considering the manual process of preparing it, they felt it will be difficult and time consuming to prepare. This is supported by some of the suggestion they made that:

> "*The manual means of preparing the fibres will be time consuming, so it will help if mechanical means can be used to save time*".

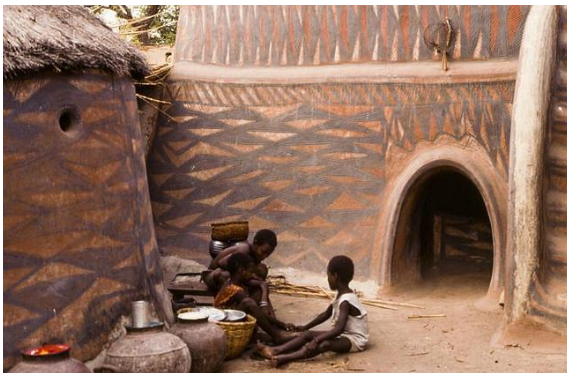
Some respondents also gave these suggestions as quoted below:

"*The fibre enhanced soil blocks will be more useful in the rural areas*"

"*You must try to implement this research work to help our rural communities especially the three Northern Regions*"

This suggests that some of the respondents were of the opinion that the enhanced soil blocks will be more useful in the rural areas where earthen construction is common. Therefore, introducing the technique in rural Ghana communities will be more accepted than the urban communities where conventional building materials for building houses dominate. There are ten regions in Ghana (Figure 11.2), out of which the three Northern Regions (Upper East, Upper West and the North) are the less economic developed among them, and are therefore the regions with massive earthen structures. There are some earthen structures (Figure 11.3) in these three regions which represent their values and traditional patterns.

Figure 11.2: Map of Ghana showing the ten regions
(Wikipedia, 2015)



Mud huts showing the ancient symbolic patterns of Gurunsi people in Northern Ghana *(Kwekudee, 2013)*

The oldest mosque in the Northern Ghana *(Izaak, 2012)*

Adobe fortress home of Wala people in Wa *(Naturalhomes, 2013)*

Figure 11.3: Traditional buildings showing patterns and values of Northern Ghana

11.5.3 Organisation of the workshop

The respondents agreed to the item O1 '*I am satisfied with the general organisation of the workshop*' with Mean / Standard deviation value of 4.14 ± 0.77. This means that the participants generally agreed that the workshop training was satisfactory organised. Similar rating was given by the respondents to the items O2 and O3 '*delivery of the workshop was satisfactory*' and '*resources provided for the workshop were helpful*' respectively. It suggests that the resources such as note pads, pens and pencils, technical guide on the production of agricultural waste fibre reinforced soil blocks, posters, among others were helpful to the delivery of the workshop training. Though the participant felt the organisation and the resources provided were good, some of them gave this suggestion as quoted below:

> "*The delivery of the workshop was good, but next time try and used overhead projector instead of posters*"

This means although the posters were good, the use of project could sustain the interest of the participants in the workshop training with the changing of slides, which will show different viewing characteristics.

11.5.4 Further suggestions and recommendations from the participants

The respondents of the workshop training in addition to the above mentioned made the following additional comments and suggestions:

- *Addition of binders like cement and POP into the reinforced soil blocks will help to make it more durable*
- *The fibres must be improved and package like cement to make it available in market for people to buy and used for construction of their houses*
- *The technique is a good idea and must be encouraged, keep it up*
- *Further research must be done to test the fire resistance of the fibre reinforced soil blocks*
- *I believe if the demand for the fibres increased, the farmers will not leave the waste but will sell them, which will increase the cost of the fibres*
- *The compression machine used for making the blocks should be made available in the rural communities for use, so that they will not continue to use the wooden moulds*
- *This idea should be extended to technical and vocational school to help train the students*
- *Very good research and I have learnt a new idea from the workshop*
- *The blocks might have good thermal properties as well*
- *Additives can be added to check insert or termite attack*
- *Government intervention is needed to promote the idea*
- *Other wastes must be researched to be used to reinforced the soil blocks*

From the above, it can been seen that the participants commended the research work and stated that the idea is good and must be encouraged. In view of this, some suggested the idea should be included in the curriculum of technical and vocational schools to inculcate the idea of developing local available materials into the students, and also to seek government intervention in promoting the research. Some participants also suggested the introduction of other additive for checking termites and rodents and some binders to increase durability properties of the fibre enhanced soil blocks. Improvement of the fibres in the form of bagging it (like cement) was also suggested for others to have access to the fibres, contrarily, others expressed that if the demand for the fibre increase, it might lead to increase cost like in the case of cement. In addition, some suggested the need for further research work in using other waste materials and fire resistance and thermal properties tests.

11.6 SUMMARY

This chapter presented how the outcome of the research project was planned and disseminated to both the academic and non-academic environment. It extended the impact of the research to the local communities in rural Ghana where earthen construction is predominant. The benefits of the study to various beneficiary groups were discussed, taking into consideration clients, builders and researchers/students. The social-economic contribution and challenges of the construction industry in Ghana have been discussed. The informal construction sector in Ghana and how it operates was also presented. Strategies for maximising the impact of the study were carried out by organising focused group workshop training on the preparation of the fibre reinforced soil blocks and their benefits for earth construction master masons. Finally, the participants of workshop training responses to questionnaire on the benefits of the fibre enhanced soil blocks and the organisation of the workshop were evaluated.

PART V

CONCLUSION AND RECOMMENDATIONS

CHAPTER 12

12 CONCLUSION AND RECOMMENDATIONS

12.1 INTRODUCTION

This chapter presents the concluding summary and recommendations for the research. The aim of this chapter is to summarise the findings of the research and make recommendations for use of the enhanced soil blocks to earth construction practitioners and to researchers for further works.

12.2 SUMMARY CONCLUSION

This work extends the existing database of different fibres used for reinforcement of building soils blocks by using different agricultural waste fibres in different soil types. The aim of this research was to investigate the properties and internal mechanism of novel soil blocks made with three different agricultural waste fibres in two different soil types for producing low-cost housing in a developing country context with particular reference to Ghana. The conclusion is presented based on the findings of the experimental work and impact dissemination assessment which have direct link to the objectives of the study.

The findings of the experimental investigations on the properties of soil types used for the research work were reported in Chapter 4. On the basis of the results obtained for all the three experimental soils, it can be concluded that the properties and characteristics of soil samples were suitable to be used for making soil blocks. Although soil R clay content was found to be higher than the recommendation by Houben and Guillaud (1994), the general properties and characteristics made it suitable to be used for making soil blocks.

The outcome of the experimental investigations on the properties of the agricultural waste fibres used as reinforcement of soil blocks were reported in Chapter 5. From the findings, the investigation concludes that different fibres have different properties and behave similarly in wet and damp conditions. However, all the fibre types (coconut, bagasse and oil palm) possess a good estimates for design and construction purpose as described by Ghavami et al. (1999), and are therefore suitable to be used as reinforcement in soil blocks.

The findings of the experimental investigation on the effect of compaction rate for producing soil blocks on the strength properties were reported in Chapter 6. The investigation therefore concludes that although the low rate of compaction achieved slightly better performance characteristics, there was not a statistically significant difference between the soil blocks produced with low compaction rate and high compaction rate. This means there is no serious need to control the compaction rate of making the soil blocks.

Some of the issues identified in the pre-test investigation were related to the methodology used. These include: (1) the need for ensure uniform mixing of the materials, (2) the need to ensure appropriate means of removing specimen from mould, (3) filling of mould with one layer of mix instead of number of layers, (4) adopt a specific compaction pressure for making the soil blocks, and (5) the use of water spray erosion test instead of Geelong test for field work.

The outcome of the experimental investigations on the effect of aspect ratio of coconut, bagasse and oil palm fibres on the mechanical properties of soil blocks were reported in Chapter 7. The investigation concludes that, in general, an increase in fibre aspect ratio has a positive effect on the strength of enhanced soil blocks. The fibre aspect ratio for all the fibre types produced a maximum strength at fibre aspect ratios of 100 and 125, which translate into fibre lengths of 50 mm, 80 mm and 38 mm for coconut, bagasse and oil palm fibres, respectively. This finding supports Halpin and Kardos (1976) assertion that reinforcing fibres for composite materials should be equal to or greater than an aspect ratio of 100. While this is generally true, it must be noted that not all fibre enhanced blocks will achieve an increased strength that the maximum aspect ratio as bagasse fibre obtained optimum compressive and tensile strengths at a slightly lower aspect ratio than the maximum. This implies that researchers and practitioners need to determine the optimum fibre aspect ratio to be used for stabilising soil blocks as well as the optimum fibre content in order to produce blocks that will provide the maximum strength for walling of houses.

The findings of the experimental investigation on the properties of soil building blocks reinforced with coconut husk fibres, oil palm nut fruit fibres and sugarcane bagasse fibres were reported in Chapter 8. The investigation concludes that, the inclusion of bagasse, coconut and oil palm fibres enhanced the properties of soil blocks. The optimum performance of the enhanced soil blocks was generally achieved at 0.5% fibre content.

Furthermore, the high clay soil performed better in all the properties of the fibre reinforced soil blocks than the low clay soil. This implies that the criteria for soil suitability which have been generally developed for binder stabilised blocks (Houben and Guillaud, 1994) are not appropriate for fibre reinforced soil blocks.

In addition, it was found that attempt to extrapolate mechanical and durability properties from physical properties will result in errors. Unlike binder stabilised blocks, which the density is inversely correlated with strength and durability. This implies that the proxy measures, such as physical properties for strength and durability of soil blocks reinforced with binders, such as Portland cement (Venkatarama Reddy and Jagadish, 1995, Walker, 2004), are not necessarily applicable for fibre reinforced soil blocks.

The internal mechanism of the interaction between fibre and soil is important to improve design of earthen structures and for wider acceptance of the composite in the formal construction industry. As Diambra et al. (2013) opined that the formal construction industry has not adopted the technology of fibre reinforcement of soils due to lack of methodical performance appraisal and understanding of the interaction mechanism between the soil and the fibre. This study has contributed to the understanding of the interaction between the fibre and soil matrix as a composite material. Summary of findings were reported in Chapter 9. It concludes that, in general, fibres in the soil matrix are randomly distributed which is good to reduce shrinkage cracking effect and also increase strength. Gaps exist between the fibres and the soil matrix. Fibres in the soil matrix undergo changes in size (diameter) which accounts for the gaps that are created in the fibre reinforced soil matrix. And fibres in soil matrix can either be pulled out or break under failure force. The interfacial peak strength of the soil matrix and the fibres' pull-out increased with increase fibre diameter.

The findings of the research were disseminated to the beneficiaries of earth construction globally. For academics, the methodology and results of the study were published in high-impact peer-reviewed journals and international conference. A technical guide on the production of fibre reinforced soil blocks was prepared and distributed to government agencies, real estate developers, builders and earth construction users in Ghana. Focus group workshop training was organised for masons in Ghana who are directly involved in supervising and constructing earthen structures, after which evaluation of the workshop training was done. Detailed report on the dissemination can be found in Chapter 10.

This work investigated the properties of soils and agricultural waste fibres used for making reinforced soil blocks, the fibre aspect ratio that produces optimum block strength, the properties of the fibre enhanced soil blocks, the internal mechanism relationship of the fibres and soil matrix as a composite material and made an impact dissemination of the findings to the beneficiaries. From the findings of the investigation, it generally concludes that the properties of soil blocks reinforced with agricultural waste fibres were enhanced, and are therefore suitable for use as a building material. This is very important for less economically developed countries, particularly Ghana, because of abundance and low-cost of coconut husk, sugarcane bagasse and oil palm fruit fibres.

12.3 RECOMMENDATIONS

Based on the findings of the study, the following recommendations for earth construction practitioners and further research are proposed.

12.3.1 Practitioners

- Although there was not a statistically significant difference between the soil blocks produced with low compaction rate and high compaction rate, the low rate of compaction achieved better performance characteristics. The study therefore suggests to practitioners of earth construction to choose low compaction rate due to its slightly better performance characteristics. Manufacturers of compressed earth block machines may also consider producing machines that do not use high rate of compaction, since it will not improve the strength properties.

- The study suggests to practitioners to use fibre lengths of 50 mm, 80 mm and 38 mm for coconut, bagasse and oil palm fibres, respectively with similar diameter and length. These lengths obtained the maximum strength of fibre reinforced soil blocks, which represent 100 or more fibre aspect ratio. Therefore, depending on the fibre diameter and length available, an aspect ratio of 100 or more will be suitable.

- It is recommended to practitioners to use 0.5wt% fibre content by weight in producing soil blocks with the selected agricultural waste fibres, since it performed generally better in both mechanical and durability properties of the fibre reinforced soil blocks.

- High clay soil is recommended to practitioners for use in producing fibre reinforced soil blocks, since the study found that their blocks performed better than low clayey soil blocks in almost all the test performed. It will also be a good idea to develop more extensive soil selection criteria for fibre reinforced soil blocks.

12.3.2 Further work

- The study showed that further improvements in mechanical performance of enhanced soil blocks may be possible with consideration of aspect ratio of the fibres. Further studies could also consider investigating into the effect of fibre aspect ratio on the durability properties of soil blocks since this is another critical determinate of the engineering properties of soil blocks. It would also be a good idea to investigate the relationship between fibre aspect ratio and block size.

- Although there was improvement in the durability properties of the fibre reinforced soil blocks over the unreinforced soil blocks, there was considerable wearing and erosion of the blocks. Further investigation with the introduction of little cement content by researchers may be undertaken to provide increased durability properties and also to control possible insert or termite attack. This was also suggested by the participants of impact dissemination workshop.

- Further investigation with the use of other agricultural waste materials may be undertaken by researchers to establish their suitability for producing enhanced soil blocks so as to advance the debate on sustainable building materials for LEDCs.

- Further work is required on the internal mechanism (with the use of advanced instrument such as CT scan, SEM, Computerised Optical Microscope, Infrared spectrum and video microscope) to study the micro properties of fibre-soil composite. This will help to establish the exact point of fibres pull-out, as the pull-out found in this study was between two fibre lengths. The effect of fibre shrinkage under pressure and with different water content could also be investigated. These are important to fully understand the interactions between the fibres and the soil matrix as a composite material.

- Furthermore, the high clay soil blocks proven better than low clayey soil blocks indicates that more work is needed on establishing soil selection guideline for fibre reinforced soil blocks.

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APPENDICES

Appendix A: Details of compaction test result

Soil B

Mass of cylinder + wet sample (Mg)	**5986**	**6116**	**6208**	**6183**	**6124**
Mass of cylinder (Mg)	4257	4257	4257	4257	4257
Mass of wet sample (Mg)	1729	1859	1951	1926	1867
Bulk Density (Mg/m^3)	1.856	1.995	2.094	2.067	2.004

Container no.	**C3**	**1D7**	**K1**	**J3**	**D4**	**X8**	**J2**	**D12***	**X1**	**D9**
Mass of Container + wet soil (Mg)	114.21	114.08	120.11	123.84	125.01	115.84	124.78	141.13	130.60	140.96
Mass of Container + Dry soil (Mg)	105.43	104.21	106.78	110.53	108.41	101.57	106.57	119.08	107.44	116.22
Mass of Container (Mg)	18.71	18.13	17.97	18.73	18.28	17.86	18.05	18.12	18.31	18.39
Mass of wet soil (Mg)	95.50	95.95	102.14	105.11	106.73	97.98	106.73	123.01	112.29	122.57
Mass of dry soil (Mg)	86.72	86.08	88.81	91.80	90.13	83.71	88.52	100.96	89.13	97.83
Mass of water (Mg)	8.78	9.87	13.33	13.31	16.60	14.27	18.21	22.05	23.16	24.74
Water content (%)	10.12	11.47	15.01	14.50	18.42	17.05	20.57	21.84	25.98	25.29
Average water content (%)	10.80		14.75		17.73		21.21		25.64	
Dry density (Mg/m^3)	1.675		1.739		1.779		1.706		1.595	

Soil R

Mass of cylinder + wet sample (gm)	**6003**	**6164**	**6246**	**6197**	**6125**
Mass of cylinder (Mg)	4257	4257	4257	4257	4257
Mass of wet sample (Mg)	1746	1907	1989	1940	1868
Bulk Density (Mg/m^3)	1.874	2.047	2.135	2.082	2.005

Container no.	**X5**	**A11**	**C14**	**X8**	**X9**	**C12***	**D8**	**X11**	**J4**	**C12**
Mass of Container + wet soil (Mg)	100.12	106.76	111.04	124.98	107.50	123.72	118.98	147.55	133.30	178.20
Mass of Container + Dry soil (Mg)	90.51	95.91	97.26	109.41	93.76	105.89	101.14	124.15	110.22	146.46
Mass of Container (Mg)	18.57	18.07	18.00	18.53	17.93	17.85	18.11	17.70	17.85	17.90
Mass of wet soil (Mg)	81.55	88.69	93.04	106.45	89.57	105.87	100.87	129.85	115.45	160.30
Mass of dry soil (Mg)	71.94	77.84	79.26	90.88	75.83	88.04	83.03	106.45	92.37	128.56

Mass of water (Mg)	9.61	10.85	13.78	15.57	13.74	17.83	17.84	23.40	23.08	31.74
Water content (%)	13.36	13.94	17.39	17.13	18.12	20.25	21.49	21.98	24.99	24.69
Average water content (%)	13.65		17.26		19.19		21.73			24.84
Dry density (Mg/m^3)	1.649		1.746		1.791		1.711			1.606

Soil HI

Mass of cylinder + wet sample (gm)	**6027.5**	**6078.5**	**6163.5**	**6257.5**	**6280.0**	**6267.0**
Mass of cylinder (Mg)	4202.5	4202.5	4203.0	4203.0	4203.5	4203.5
Mass of wet sample (Mg)	1825.0	1876.0	1960.5	2054.5	2076.5	2063.5
Bulk Density (Mg/m^3)	1.83	1.88	1.96	2.05	2.08	2.06

Container no.	**12**	**3**	**7**	**23**	**11**	**17**	**25**	**47**	**32**	**51**	**42**	**27**
Mass of Container + wet soil (Mg)	40.5	38.0	37.5	38.0	40.5	33.5	37.5	40.5	36.0	38.5	36.0	35.5
Mass of Container + Dry soil (Mg)	39.5	37.0	35.0	36.0	38.0	31.0	34.0	37.5	32.5	34.5	32.0	31.5
Mass of Container (Mg)	10.0	8.0	6.5	8.0	9.5	4.5	7.0	9.5	6.5	7.0	6.5	6.5
Mass of wet soil (Mg)	30.5	30.0	31.0	30.0	31.0	29.5	30.5	31.0	29.5	31.5	29.5	29.0
Mass of dry soil (Mg)	29.5	29.0	28.5	28.0	28.5	26.5	27.0	26.0	26.0	27.5	25.5	25.0
Water content (%)	3.39	3.45	8.77	7.14	8.77	9.43	12.96	10.71	13.46	14.55	15.69	16.00
Average water content (%)	3.42		7.96		9.10		11.80		14.00		15.80	
Dry density (Mg/m^3)	1.77		1.74		1.80		1.83		1.82		1.78	

Appendix B: Grading test details

Soil B

Total Dry Weight (g) 51.7

Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
75.00			
63.00			
53.00			
37.10			
26.50			
19.00			
13.20			
9.50			
6.70			100.0
4.75	2.67	5.2	94.83
3.35	2.98	5.8	89.07

Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
2.00	0.50	0.97	88.10
1.00	2.10	4.06	84.04
0.600	1.79	3.46	80.57
0.425	1.70	3.29	77.28
0.300	2.25	4.35	72.93
0.212	2.72	5.26	67.67
0.150	5.02	9.71	57.95
0.075	1.24	2.40	55.55

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (º c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.5	9:4	26	1.018	18.5	19.0	125.5	0.86	0.06	1.27	16.1	50.86
1	9:4	27	1.017	17.0	17.5	131.4	0.84	0.04	1.52	14.9	46.93
2	9:4	27	1.015	15.5	16.0	137.4	0.84	0.03	1.52	13.4	42.21
4	9:4	27	1.014	14.0	14.5	143.3	0.84	0.02	1.52	11.9	37.50
8	9:5	27	1.013	13.0	13.5	147.2	0.84	0.01	1.52	10.9	34.35
15	9:5	27	1.012	12.0	12.5	151.2	0.84	0.01	1.52	9.92	31.21
30	10:1	27	1.010	10.5	11.0	157.1	0.84	0.01	1.52	8.42	26.49
60	10:4	27	1.009	9.5	10.0	161.1	0.84	0.01	1.52	7.42	23.35
120	11:4	27	1.008	8.5	9.00	165.0	0.84	0.01	1.52	6.42	20.20
240	11:4	27	1.007	7.5	8.00	169.0	0.84	0.01	1.52	5.42	17.06
1440	9:4	27	1.006	6.5	7.00	172.9	0.84	0.01	1.52	4.42	13.91

Soil R

Total Dry Weight (g) 57 .4

Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
75.00			
63.00			
53.00			
37.10			
26.50			
19.00			
13.20			
9.50			
6.70			100.0
4.75	2.34	4.1	95.92
3.35	3.56	6.2	89.71

Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
2.00	2.86	4.99	84.7
1.00	3.43	5.98	78.7
0.600	1.68	2.93	75.8
0.425	1.00	1.74	74.0
0.300	1.10	1.92	72.
0.212	1.22	2.13	70.0
0.150	3.08	5.37	64.6
0.075	1.14	1.99	62.6

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (º c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.5	10:4	27	1.020	20.5	21.0	117	0.84	0.061	1.524	18.4	52.2
1	10:4	27	1.019	19.0	19.5	123	0.84	0.044	1.524	16.9	47.9
2	10:4	27	1.018	18.2	18.7	126	0.84	0.032	1.524	16.1	45.6
4	10:4	27	1.017	17.7	18.2	128	0.84	0.022	1.524	15.6	44.2
8	10:5	27	1.016	16.8	17.3	132	0.84	0.016	1.524	14.7	41.7
15	10:5	27	1.016	16.0	16.5	135	0.84	0.012	1.524	13.9	39.4
30	11:1	27	1.015	15.5	16.0	137	0.84	0.008	1.524	13.4	38.0
60	11:4	27	1.015	15.0	15.5	139	0.84	0.006	1.524	12.9	36.6
120	12:4	27	1.014	14.0	14.5	143	0.84	0.004	1.524	11.9	33.7
240	2:4	27	1.013	13.5	14.0	145	0.84	0.003	1.524	11.4	32.3
1440	10:4	27	1.012	12.5	13.0	149	0.84	0.001	1.524	10.4	29.5

Soil HI

Total Dry Weight (g) 200

Sieve size (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
5	4	2	98
3.35	2	1	97
2	14	7	90
1.18	24	12	78
0.6	14	7	71
0.425	28	14	57
0.3	18	9	48
0.212	14	7	41
0.15	24	12	33
0.063	8	4	29
0.02	8	4	25
0.006	18	9	16
0.002	10	5	11
0.0006	2	1	10
0.0002	20	10	0

Appendix C: Atterberg limits test details

Soil B

Liquid Limit					
Container No.	C17	X5	B17	A20	B37
Mass of container	3.60	3.65	3.69	3.59	3.78
Penetration	8.70	12.65	16.20	21.65	28.15
Mass of wet sample + container	21.13	27.43	31.39	29.24	34.19
Mass of dry sample + container	17.81	22.44	25.18	23.08	26.05
Mass of water	3.32	4.99	6.21	6.16	8.14
Mass of dry sample	14.21	18.79	21.49	19.49	22.27
Water content %	23.36	26.56	28.90	31.61	36.55
Plastic Limit					
Container No.	B38	C28			
Mass of container	3.57	3.78			
Mass of wet sample + container	18.85	20.08			
Mass of dry sample + container	16.61	17.68			
Mass of water	2.24	2.4			
Mass of dry sample	13.04	13.9			
Water content %	17.18	17.27	LL	PL	PI
Mean water content %	17.22		31.1	17.2	13.9

Soil R

Liquid Limit					
Container No.	A20	A10	A1	E3	B15
Mass of container	3.67	3.85	3.73	3.57	3.70
Penetration	8.20	11.05	18.65	22.50	26.00
Mass of wet sample + container	22.44	24.57	29.50	26.77	36.33
Mass of dry sample + container	17.23	18.38	20.86	18.62	24.55
Mass of water	5.21	6.19	8.64	8.15	11.78
Mass of dry sample	13.56	14.53	17.13	15.05	20.85
Water content %	38.42	42.60	50.44	54.15	56.50
Plastic Limit					
Container No.	C8	X15			
Mass of container	3.68	3.75			
Mass of wet sample + container	16.30	17.05			
Mass of dry sample + container	13.59	14.20			
Mass of water	2.71	2.85			
Mass of dry sample	9.91	10.45			
Water content %	27.35	27.27	LL	PL	PI
Mean water content %	27.31		51.2	27.3	23.9

Soil HI

Liquid Limit					
Container No.	63	72	44	50	68
Mass of container	3.60	3.65	3.69	3.59	3.78
Penetration	8.70	12.65	16.20	21.65	28.15
Mass of wet sample + container	21.13	27.43	31.39	29.24	34.19
Mass of dry sample + container	17.81	22.44	25.18	23.08	26.05
Mass of water	3.32	4.99	6.21	6.16	8.14
Mass of dry sample	14.21	18.79	21.49	19.49	22.27
Water content %	30.9	32.5	31.7	31.2	32.2
Plastic Limit					
Container No.	12	47			
Mass of container	3.57	3.78			
Mass of wet sample + container	18.85	20.08			
Mass of dry sample + container	16.61	17.68			
Mass of water	2.24	2.4			
Mass of dry sample	13.04	13.9			
Water content %	17.7	18.3	LL	PL	PI
Mean water content %	18.0		31.7	18.0	13.7

Appendix D: Moisture content of soil samples

Soil type	m_1 (g)	m_2 (g)	Mm (g)	MC (%)
B	35.76	116.94	109.7	9.8
	35.42	112.25	106.16	8.6
	37.16	110.68	104.11	9.8
	36.28	107.34	101.46	9.0
	35.98	111.72	104.98	9.8
Ave	**36.12**	**111.79**	**105.28**	**9.4**
St Dev	**0.66**	**3.46**	**3.02**	**0.6**
R	35.70	116.02	108.23	10.7
	36.87	109.41	102.38	10.7
	35.47	104.57	98.04	10.4
	35.80	112.43	105.69	9.6
	36.03	101.35	95.31	10.2
Ave	**35.97**	**108.76**	**101.93**	**10.3**
St Dev	**0.54**	**5.90**	**5.31**	**0.5**
HI	8.31	85.90	79.72	8.7
	5.92	83.32	77.34	8.4
	6.71	84.53	78.12	9.0
	8.34	86.31	79.76	9.1
	5.86	83.22	77.28	8.3
Ave	**7.03**	**84.66**	**78.44**	**8.7**
St Dev	**1.23**	**1.43**	**1.23**	**0.4**

Appendix E: Compaction rate test results

Compaction rate (mm/min)	Test			
	Dry Density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Drip erosion (mm)
1	1931	3.10	0.43	6.00
	1895	3.50	0.48	7.50
	1857	3.20	0.57	5.00
Ave	**1894**	**3.30**	**0.49**	**6.20**
St Dev	**37**	**0.21**	**0.07**	**1.26**
5	1925	3.70	0.29	8.00
	1899	2.70	0.47	6.00
	1845	2.60	0.48	7.00
Ave	**1890**	**3.00**	**0.41**	**7.00**
St Dev	**41**	**0.61**	**0.11**	**1.00**
10	1904	2.40	0.34	7.00
	1872	3.20	0.56	9.00
	1821	2.70	0.49	6.00
Ave	**1866**	**2.80**	**0.46**	**7.30**
St Dev	**42**	**0.40**	**0.11**	**1.53**
15	1916	2.50	0.36	8.00
	1873	3.10	0.44	7.00
	1825	2.70	0.42	9.50
Ave	**1871**	**2.70**	**0.41**	**8.20**
St Dev	**46**	**0.31**	**0.04**	**1.26**

Appendix F: Compressive and tensile strength test result for aspect ratio

Aspect ratio	Compressive strength (MPa)			Compressive strength (MPa)		
	Coconut	Bagasse	Oil palm	Coconut	Bagasse	Oil palm
25	-	-	0.94	-	-	0.28
	-	-	0.98	-	-	0.25
	-	-	0.96	-	-	0.24
	-	-	1.00	-	-	0.25
	-	-	0.93	-	-	0.23
Ave	**-**	**-**	**0.96**	**-**	**-**	**0.25**
St Dev	**-**	**-**	**0.03**	**-**	**-**	**0.02**
50	1.12	0.78	0.99	0.20	0.19	0.25
	1.01	0.81	1.02	0.17	0.20	0.27
	1.14	0.82	1.00	0.15	0.22	0.25
	0.98	0.90	1.00	0.18	0.20	0.26
	1.10	0.84	1.01	0.17	0.21	0.27
Ave	**1.07**	**0.83**	**1.00**	**0.18**	**0.21**	**0.26**
St Dev	**0.07**	**0.05**	**0.01**	**0.02**	**0.01**	**0.01**
75	1.10	0.90	1.16	0.25	0.25	0.30
	1.17	0.98	1.12	0.22	0.23	0.28
	1.12	0.89	1.03	0.23	0.20	0.27
	1.19	0.93	1.05	0.23	0.24	0.29
	1.22	0.98	1.12	0.26	0.22	0.30
Ave	**1.16**	**0.94**	**1.10**	**0.24**	**0.23**	**0.29**
St Dev	**0.05**	**0.04**	**0.05**	**0.02**	**0.02**	**0.01**
100	1.25	1.07	1.13	0.25	0.29	0.33
	1.23	1.12	1.15	0.28	0.27	0.31
	1.27	1.13	1.17	0.26	0.26	0.29
	1.21	1.10	1.14	0.24	0.28	0.27
	1.29	1.07	1.12	0.25	0.29	0.30
Ave	**1.25**	**1.10**	**1.14**	**0.26**	**0.28**	**0.30**
St Dev	**0.03**	**0.03**	**0.02**	**0.01**	**0.01**	**0.02**
125	1.36	1.05	-	0.26	0.26	-
	1.29	1.01	-	0.29	0.25	-
	1.36	1.08	-	0.32	0.28	-
	1.35	1.02	-	0.25	0.26	-
	1.39	1.09	-	0.31	0.27	-
Ave	**1.35**	**1.05**	**-**	**0.29**	**0.26**	**-**
St Dev	**0.04**	**0.03**	**-**	**0.03**	**0.01**	**-**

Appendix G: Physical Properties of enhanced soil blocks

(0% fibre)

Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Red	0.287	0.139	0.101	0.00403	7.772	8.811	1929	8.1	1.05
	0.287	0.139	0.1	0.00399	7.702	8.661	1931	7.5	1.05
	0.288	0.137	0.102	0.00402	7.982	8.944	1983	7.5	0.69
	0.286	0.138	0.1	0.00395	7.811	8.897	1979	8.5	1.40
	0.287	0.139	0.101	0.00403	7.798	8.94	1935	8.9	1.05
Ave	**0.287**	**0.138**	**0.101**	**0.00400**	**7.813**	**8.851**	**1951**	**8.1**	**1.05**
St Dev	**0.0007**	**0.0009**	**0.0008**	**0.00004**	**0.103**	**0.119**	**27**	**0.6**	**0.25**
Brown	0.287	0.138	0.101	0.00400	7.535	8.735	1884	9.3	1.05
	0.288	0.139	0.102	0.00408	7.789	8.87	1908	8.4	0.69
	0.287	0.137	0.101	0.00397	7.505	8.664	1890	9.0	1.05
	0.287	0.137	0.102	0.00401	7.730	8.783	1927	8.2	1.05
	0.288	0.139	0.1	0.00400	7.752	8.722	1936	7.6	0.69
Ave	**0.2874**	**0.138**	**0.101**	**0.00401**	**7.662**	**8.755**	**1909**	**8.5**	**0.90**
St Dev	**0.0005**	**0.0010**	**0.0008**	**0.00004**	**0.132**	**0.077**	**23**	**0.7**	**0.19**

(0.25% fibre)

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Bagasse Red soil	0.288	0.138	0.104	0.00413	7.654	8.924	1852	9.9	0.69
	0.288	0.139	0.102	0.00408	7.78	9.166	1905	10.8	0.69
	0.287	0.138	0.104	0.00412	7.601	8.824	1845	9.5	1.05
	0.288	0.139	0.103	0.00412	7.634	9.047	1851	11.0	0.69
	0.287	0.139	0.104	0.00415	7.798	9.194	1880	10.9	1.05
Ave	**0.288**	**0.139**	**0.103**	**0.00412**	**7.6934**	**9.031**	**1867**	**10.4**	**0.83**
St Dev	**0.0005**	**0.0005**	**0.0009**	**0.00002**	**0.090**	**0.158**	**25**	**0.7**	**0.19**
Bagasse Brown soil	0.287	0.139	0.103	0.00411	7.602	8.965	1850	10.6	1.05
	0.288	0.138	0.104	0.00413	7.709	9.184	1865	11.5	0.69
	0.289	0.139	0.104	0.00418	7.613	8.898	1822	10.0	0.35
	0.287	0.138	0.103	0.00408	7.643	9.122	1874	11.5	1.05
	0.288	0.138	0.102	0.00405	7.672	9.046	1893	10.7	0.69
Ave	**0.288**	**0.138**	**0.103**	**0.00411**	**7.648**	**9.043**	**1861**	**10.9**	**0.77**
St Dev	**0.0008**	**0.0005**	**0.0008**	**0.00005**	**0.044**	**0.115**	**26**	**0.6**	**0.29**
Coconut Red soil	0.288	0.138	0.102	0.00405	7.680	8.89	1894	9.4	0.69
	0.287	0.139	0.103	0.00411	7.653	9.01	1863	10.6	1.05
	0.288	0.139	0.103	0.00412	7.640	8.789	1853	8.9	0.69
	0.288	0.138	0.104	0.00413	7.599	8.87	1838	9.9	0.69
	0.287	0.139	0.104	0.00415	7.620	8.93	1837	10.2	1.05
Ave	**0.288**	**0.139**	**0.103**	**0.00411**	**7.6384**	**8.898**	**1857**	**9.8**	**0.83**

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
St Dev	**0.0005**	**0.0005**	**0.0008**	**0.00004**	**0.031**	**0.081**	**24**	**0.6**	**0.19**
Coconut Brown soil	0.288	0.139	0.104	0.00416	7.680	8.894	1845	9.5	0.69
	0.287	0.139	0.103	0.00411	7.625	8.978	1856	10.5	1.05
	0.288	0.138	0.102	0.00405	7.596	8.898	1874	10.1	0.69
	0.287	0.139	0.104	0.00415	7.607	8.95	1834	10.5	1.05
	0.289	0.139	0.104	0.00418	7.589	8.96	1817	10.7	0.35
Ave	**0.2878**	**0.1388**	**0.103**	**0.00413**	**7.619**	**8.936**	**1845**	**10.3**	**0.77**
St Dev	**0.0008**	**0.0004**	**0.0009**	**0.00005**	**0.037**	**0.038**	**22**	**0.5**	**0.29**
Oil Palm Red soil	0.287	0.139	0.103	0.00411	7.710	8.93	1876	9.5	1.05
	0.288	0.139	0.102	0.00408	7.700	8.95	1886	9.7	0.69
	0.287	0.139	0.102	0.00407	7.640	8.83	1878	9.3	1.05
	0.288	0.138	0.103	0.00409	7.789	8.96	1903	9.1	0.69
	0.288	0.139	0.102	0.00408	7.775	8.96	1904	9.2	0.69
Ave	**0.288**	**0.139**	**0.102**	**0.00409**	**7.7228**	**8.926**	**1889**	**9.4**	**0.83**
St Dev	**0.0005**	**0.0004**	**0.0005**	**0.00001**	**0.061**	**0.055**	**13**	**0.2**	**0.19**
Oil Palm Brown soil	0.288	0.139	0.102	0.00408	7.698	8.96	1885	9.8	0.69
	0.288	0.138	0.103	0.00409	7.691	8.886	1879	9.3	0.69
	0.287	0.138	0.102	0.00404	7.632	8.868	1889	9.6	1.05
	0.288	0.139	0.103	0.00412	7.779	8.997	1887	9.5	0.69
	0.288	0.139	0.102	0.00408	7.69	8.985	1883	10.1	0.69
Ave	**0.2878**	**0.1386**	**0.102**	**0.00408**	**7.698**	**8.939**	**1885**	**9.7**	**0.76**
St Dev	**0.0004**	**0.0005**	**0.0005**	**0.00003**	**0.053**	**0.059**	**4**	**0.3**	**0.16**

(0.5% fibre)

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Bagasse Red soil	0.288	0.139	0.104	0.00416	7.456	8.89	1791	11.2	0.69
	0.289	0.138	0.102	0.00407	7.617	9.20	1872	12.3	0.35
	0.288	0.138	0.104	0.00413	7.410	8.97	1793	12.2	0.69
	0.288	0.138	0.103	0.00409	7.390	9.13	1805	13.6	0.69
	0.288	0.137	0.104	0.00410	7.570	9.20	1845	12.7	0.69
Ave	**0.288**	**0.138**	**0.103**	**0.00411**	**7.4886**	**9.078**	**1821**	**12.4**	**0.62**
St Dev	**0.0004**	**0.0007**	**0.0009**	**0.00004**	**0.100**	**0.141**	**36**	**0.9**	**0.16**
Bagasse Brown soil	0.288	0.138	0.103	0.00409	7.450	8.99	1820	12.0	0.69
	0.289	0.139	0.104	0.00418	7.580	9.23	1814	12.9	0.35
	0.288	0.138	0.104	0.00413	7.345	8.98	1777	12.7	0.69
	0.288	0.139	0.103	0.00412	7.410	9.21	1797	14.0	0.69
	0.289	0.138	0.1	0.00399	7.213	8.98	1809	13.8	0.35
Ave	**0.288**	**0.138**	**0.103**	**0.00410**	**7.400**	**9.078**	**1803**	**13.1**	**0.56**
St Dev	**0.0005**	**0.0005**	**0.0016**	**0.00007**	**0.135**	**0.130**	**17**	**0.8**	**0.19**

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Coconut Red soil	0.288	0.138	0.103	0.00409	7.59	8.97	1854	10.8	0.69
	0.287	0.138	0.103	0.00408	7.53	9.12	1846	12.4	1.05
	0.288	0.139	0.102	0.00408	7.513	8.99	1840	11.5	0.69
	0.288	0.138	0.104	0.00413	7.335	8.98	1775	12.8	0.69
	0.289	0.138	0.103	0.00411	7.53	9.03	1833	11.7	0.35
Ave	**0.288**	**0.138**	**0.103**	**0.00410**	**7.4996**	**9.019**	**1830**	**11.8**	**0.69**
St Dev	**0.0007**	**0.0004**	**0.0007**	**0.00002**	**0.097**	**0.061**	**32**	**0.8**	**0.25**
Coconut Brown soil	0.288	0.139	0.102	0.00408	7.53	9.098	1844	12.2	0.69
	0.288	0.139	0.103	0.00412	7.523	9.183	1825	12.9	0.69
	0.288	0.138	0.104	0.00413	7.510	9.045	1817	12.0	0.69
	0.289	0.139	0.104	0.00418	7.520	9.251	1800	13.5	0.35
	0.288	0.138	0.103	0.00409	7.450	9.123	1820	13.0	0.69
Ave	**0.2882**	**0.1386**	**0.103**	**0.00412**	**7.507**	**9.140**	**1821**	**12.7**	**0.62**
St Dev	**0.0004**	**0.0005**	**0.0008**	**0.00004**	**0.032**	**0.079**	**16**	**0.6**	**0.16**
Oil Palm Red soil	0.288	0.138	0.102	0.00405	7.570	8.93	1867	10.6	0.69
	0.287	0.137	0.102	0.00401	7.626	8.95	1901	10.3	1.05
	0.288	0.138	0.101	0.00401	7.553	8.83	1882	9.9	0.69
	0.288	0.138	0.101	0.00401	7.680	8.96	1913	10.0	0.69
	0.288	0.137	0.102	0.00402	7.551	8.96	1876	11.0	0.69
Ave	**0.288**	**0.138**	**0.102**	**0.00402**	**7.596**	**8.926**	**1888**	**10.4**	**0.76**
St Dev	**0.0004**	**0.0005**	**0.0005**	**0.00002**	**0.056**	**0.055**	**19**	**0.4**	**0.16**
Oil Palm Brown soil	0.288	0.137	0.102	0.00402	7.503	8.989	1864	11.6	0.69
	0.288	0.138	0.101	0.00401	7.542	8.987	1879	11.3	0.69
	0.289	0.137	0.102	0.00404	7.512	8.98	1860	11.4	0.35
	0.288	0.137	0.102	0.00402	7.511	8.93	1866	11.1	0.69
	0.288	0.138	0.101	0.00401	7.530	8.87	1876	10.4	0.69
Ave	**0.2882**	**0.1374**	**0.102**	**0.00402**	**7.520**	**8.951**	**1869**	**11.2**	**0.62**
St Dev	**0.0004**	**0.0005**	**0.0005**	**0.00001**	**0.016**	**0.051**	**8**	**0.4**	**0.16**

(0.75% fibre)

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Bagasse Red soil	0.288	0.138	0.104	0.00413	7.571	9.213	1832	12.8	0.69
	0.288	0.139	0.104	0.00416	7.601	9.462	1826	14.5	0.69
	0.289	0.139	0.104	0.00418	7.541	9.371	1805	14.3	0.35
	0.288	0.139	0.105	0.00420	7.612	9.508	1811	14.8	0.69
	0.289	0.138	0.104	0.00415	7.544	9.367	1819	14.2	0.35
Ave	**0.288**	**0.139**	**0.104**	**0.00417**	**7.5738**	**9.384**	**1818**	**14.1**	**0.56**
St Dev	**0.0005**	**0.0005**	**0.0004**	**0.00003**	**0.032**	**0.113**	**11**	**0.8**	**0.19**
	0.289	0.138	0.104	0.00415	7.512	9.485	1811	15.4	0.35

Fibre/ Soil Type	Dimension (mm) Length	Width	Thick-ness	Volume/weight Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Test Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Bagasse	0.288	0.139	0.104	0.00416	7.522	9.567	1807	15.9	0.69
	0.289	0.139	0.104	0.00418	7.42	9.390	1776	15.3	0.35
Brown soil	0.288	0.139	0.103	0.00412	7.464	9.404	1810	15.1	0.69
	0.289	0.138	0.104	0.00415	7.426	9.387	1790	15.3	0.35
Ave	**0.2886**	**0.1386**	**0.104**	**0.00415**	**7.469**	**9.447**	**1799**	**15.4**	**0.49**
St Dev	**0.0005**	**0.0005**	**0.0004**	**0.00002**	**0.047**	**0.078**	**15**	**0.3**	**0.19**
Coconut	0.288	0.138	0.104	0.00413	7.523	9.370	1820	14.4	0.69
	0.289	0.138	0.103	0.00411	7.501	9.312	1826	14.1	0.35
Red soil	0.288	0.139	0.104	0.00416	7.513	9.322	1805	14.1	0.69
	0.288	0.138	0.104	0.00413	7.466	9.156	1806	13.2	0.69
	0.289	0.138	0.103	0.00411	7.513	9.112	1829	12.5	0.35
Ave	**0.288**	**0.138**	**0.104**	**0.00413**	**7.5032**	**9.254**	**1817**	**13.6**	**0.56**
St Dev	**0.0005**	**0.0004**	**0.0005**	**0.00002**	**0.022**	**0.113**	**11**	**0.8**	**0.19**
Coconut	0.288	0.139	0.104	0.00416	7.530	9.413	1809	14.7	0.69
	0.289	0.139	0.103	0.00414	7.523	9.331	1818	14.1	0.35
Brown soil	0.288	0.138	0.102	0.00405	7.51	9.374	1853	14.5	0.69
	0.289	0.139	0.104	0.00418	7.520	9.482	1800	15.3	0.35
	0.289	0.139	0.104	0.00418	7.450	9.311	1783	14.5	0.35
Ave	**0.2886**	**0.1388**	**0.103**	**0.00414**	**7.507**	**9.382**	**1813**	**14.6**	**0.49**
St Dev	**0.0005**	**0.0004**	**0.0009**	**0.00005**	**0.032**	**0.068**	**26**	**0.4**	**0.19**
Oil Palm	0.288	0.139	0.103	0.00412	7.607	9.201	1845	12.4	0.69
	0.289	0.139	0.102	0.00410	7.583	9.098	1851	11.8	0.35
Red soil	0.288	0.138	0.103	0.00409	7.621	9.267	1862	12.8	0.69
	0.288	0.139	0.103	0.00412	7.572	9.121	1836	12.1	0.69
	0.289	0.138	0.103	0.00411	7.612	9.213	1853	12.5	0.35
Ave	**0.288**	**0.139**	**0.103**	**0.00411**	**7.599**	**9.180**	**1849**	**12.3**	**0.56**
St Dev	**0.0005**	**0.0005**	**0.0004**	**0.00001**	**0.021**	**0.069**	**9**	**0.4**	**0.19**
Oil Palm	0.289	0.138	0.103	0.00411	7.503	9.302	1827	14.0	0.35
	0.288	0.138	0.103	0.00409	7.542	9.336	1842	14.0	0.69
Brown soil	0.289	0.139	0.102	0.00410	7.512	9.287	1833	13.8	0.35
	0.289	0.138	0.103	0.00411	7.511	9.299	1828	13.9	0.35
	0.289	0.139	0.102	0.00410	7.530	9.32	1838	13.9	0.35
Ave	**0.289**	**0.138**	**0.103**	**0.00410**	**7.520**	**9.309**	**1834**	**13.9**	**0.42**
St Dev	**0.0004**	**0.0005**	**0.0005**	**0.00001**	**0.016**	**0.019**	**7**	**0.1**	**0.16**

(1% fibre)

Fibre/ Soil Type	Dimension (mm) Length	Width	Thick-ness	Volume/weight Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Test Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Bagasse	0.289	0.139	0.105	0.00422	7.592	9.643	1800	16.0	0.35
	0.288	0.139	0.104	0.00416	7.546	9.552	1812	15.6	0.69

Fibre/ Soil Type	Dimension (mm)			Volume/weight			Test		
	Length	Width	Thick-ness	Volume (m^3)	Dry Weight (kg)	Wet weight (kg)	Dry Density (kg/m^3)	Water Absorption (%)	Linear Shrinkage (%)
Red soil	0.289	0.139	0.104	0.00418	7.538	9.521	1804	15.4	0.35
	0.288	0.138	0.105	0.00417	7.600	9.671	1821	16.1	0.69
	0.289	0.139	0.104	0.00418	7.524	9.518	1801	15.5	0.35
Ave	**0.2886**	**0.1388**	**0.104**	**0.00418**	**7.560**	**9.581**	**1808**	**15.7**	**0.49**
St Dev	**0.0005**	**0.0004**	**0.001**	**0.00002**	**0.034**	**0.071**	**9**	**0.3**	**0.19**
Bagasse Brown soil	0.289	0.139	0.104	0.00418	7.533	9.654	1803	16.5	0.35
	0.289	0.139	0.105	0.00422	7.521	9.642	1783	16.5	0.35
	0.289	0.139	0.104	0.00418	7.470	9.577	1788	16.4	0.35
	0.288	0.139	0.104	0.00416	7.424	9.552	1783	16.6	0.69
	0.289	0.138	0.104	0.00415	7.436	9.529	1793	16.3	0.35
Ave	**0.2888**	**0.1388**	**0.104**	**0.00418**	**7.477**	**9.591**	**1790**	**16.5**	**0.42**
St Dev	**0.0004**	**0.0005**	**0.000**	**0.00003**	**0.049**	**0.055**	**8**	**0.1**	**0.16**
Coconut Red soil	0.289	0.139	0.104	0.00418	7.51	9.417	1798	14.9	0.35
	0.288	0.138	0.104	0.00413	7.489	9.385	1812	14.8	0.69
	0.289	0.139	0.105	0.00422	7.504	9.407	1779	14.8	0.35
	0.288	0.139	0.104	0.00416	7.500	9.409	1801	14.9	0.69
	0.289	0.138	0.105	0.00419	7.475	9.372	1785	14.8	0.35
Ave	**0.2886**	**0.1386**	**0.104**	**0.00418**	**7.4956**	**9.398**	**1795**	**14.8**	**0.49**
St Dev	**0.0005**	**0.0006**	**0.001**	**0.00003**	**0.014**	**0.019**	**13**	**0.0**	**0.19**
Coconut Brown soil	0.289	0.139	0.104	0.00418	7.310	9.323	1750	15.7	0.35
	0.288	0.139	0.104	0.00416	7.415	9.34	1781	15.0	0.69
	0.289	0.139	0.104	0.00418	7.352	9.331	1760	15.4	0.35
	0.289	0.138	0.103	0.00411	7.409	9.364	1804	15.2	0.35
	0.289	0.139	0.104	0.00418	7.378	9.32	1766	15.1	0.35
Ave	**0.2888**	**0.1388**	**0.104**	**0.00416**	**7.373**	**9.336**	**1772**	**15.3**	**0.42**
St Dev	**0.0004**	**0.0005**	**0.0004**	**0.00003**	**0.043**	**0.018**	**21**	**0.3**	**0.16**
Oil Palm Red soil	0.289	0.139	0.103	0.00414	7.569	9.31	1829	13.6	0.35
	0.289	0.139	0.104	0.00418	7.57	9.369	1812	14.0	0.35
	0.289	0.139	0.103	0.00414	7.562	9.317	1828	13.7	0.35
	0.288	0.139	0.104	0.00416	7.541	9.273	1811	13.5	0.69
	0.289	0.138	0.103	0.00411	7.536	9.249	1835	13.3	0.35
Ave	**0.2888**	**0.1388**	**0.103**	**0.00414**	**7.5556**	**9.304**	**1823**	**13.6**	**0.42**
St Dev	**0.0004**	**0.0004**	**0.001**	**0.00003**	**0.016**	**0.046**	**11**	**0.3**	**0.16**
Oil Palm Brown soil	0.289	0.139	0.103	0.00414	7.472	9.298	1806	14.2	0.35
	0.289	0.138	0.103	0.00411	7.448	9.286	1813	14.3	0.35
	0.289	0.139	0.104	0.00418	7.500	9.305	1795	14.1	0.35
	0.289	0.138	0.103	0.00411	7.460	9.29	1816	14.3	0.35
	0.289	0.139	0.104	0.00418	7.441	9.297	1781	14.5	0.35
Ave	**0.2890**	**0.1386**	**0.103**	**0.00414**	**7.464**	**9.295**	**1802**	**14.3**	**0.35**
St Dev	**0.0000**	**0.0005**	**0.001**	**0.00004**	**0.023**	**0.007**	**14**	**0.1**	**0.00**

Appendix H: Mechanical properties of enhanced soil blocks

(0% fibre)

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Bagasse Red soil	7.93	88.1	2.17	7.86	10.6	0.26
	7.90	86.4	2.13	8.00	10.7	0.26
	8.00	88.9	2.19	7.92	10.3	0.25
	7.92	84.8	2.09	8.01	11.1	0.27
	8.09	83.2	2.05	7.98	10.4	0.25
Ave	**7.968**	**86.28**	**2.13**	**7.954**	**10.62**	**0.26**
St Dev	**0.078**	**2.338**	**0.06**	**0.063**	**0.311**	**0.01**
Bagasse Brown soil	7.89	68.9	1.70	7.98	10.2	0.25
	8.04	70.0	1.72	7.83	10.1	0.25
	7.80	68.9	1.70	7.78	9.6	0.23
	7.99	69.3	1.71	7.82	9.2	0.22
	8.02	69.8	1.72	8.03	10.5	0.26
Ave	**7.948**	**69.38**	**1.71**	**7.888**	**9.92**	**0.24**
St Dev	**0.101**	**0.507**	**0.01**	**0.110**	**0.462**	**0.01**

(0.25% fibre)

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Bagasse Red soil	8.01	98.3	2.42	7.97	11.1	0.27
	7.98	97.6	2.40	8.05	11.8	0.29
	8.10	102.8	2.53	7.93	11.3	0.28
	8.04	97.4	2.40	7.95	11.4	0.28
	7.96	99.7	2.46	8.01	11.5	0.28
Ave	**8.018**	**99.2**	**2.4**	**7.982**	**11.4**	**0.28**
St Dev	**0.055**	**2.226**	**0.05**	**0.048**	**0.259**	**0.01**
Bagasse Brown soil	7.98	82.1	2.02	7.96	10.6	0.26
	8.02	83.4	2.05	7.94	10.9	0.27
	7.94	82.5	2.03	8.02	11.2	0.27
	8.06	83.4	2.05	7.97	11.0	0.27
	7.90	81.8	2.01	8.04	10.8	0.26
Ave	**7.98**	**82.6**	**2.0**	**7.986**	**10.9**	**0.27**
St Dev	**0.063**	**0.737**	**0.02**	**0.042**	**0.224**	**0.01**
Coconut Red soil	7.97	117.7	2.90	7.90	12.6	0.31
	8.00	118.1	2.91	7.88	13.3	0.32
	8.04	119.5	2.94	8.00	13.1	0.32
	7.89	118.0	2.91	8.01	12.8	0.31
	8.02	118.5	2.92	8.03	13.0	0.32
Ave	**7.984**	**118.4**	**2.92**	**7.96**	**13.0**	**0.32**

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
St Dev	**0.059**	**0.699**	**0.02**	**0.069**	**0.270**	**0.01**
Coconut Brown soil	7.92	108.7	2.68	8.04	12.6	0.31
	8.06	109.4	2.69	7.93	13.1	0.32
	8.00	109.1	2.69	7.99	11.7	0.29
	7.90	108.8	2.68	8.00	12.4	0.30
	8.01	109.3	2.69	8.01	13.0	0.32
Ave	**7.978**	**109.1**	**2.69**	**7.994**	**12.6**	**0.31**
St Dev	**0.066**	**0.305**	**0.01**	**0.040**	**0.559**	**0.01**
Oil Palm Red soil	8.00	123.1	3.03	7.90	14.4	0.35
	7.92	122.5	3.02	8.01	15.0	0.37
	8.00	122.8	3.02	7.93	14.3	0.35
	8.08	123.0	3.03	8.06	14.9	0.36
	7.90	122.9	3.03	7.96	14.2	0.35
Ave	**7.98**	**122.9**	**3.03**	**7.97**	**14.6**	**0.35**
St Dev	**0.072**	**0.230**	**0.01**	**0.064**	**0.365**	**0.01**
Oil Palm Brown soil	7.97	105.7	2.60	7.95	14.1	0.34
	8.02	106.3	2.62	8.07	13.3	0.32
	8.00	106.2	2.62	7.96	13.6	0.33
	7.89	106.0	2.61	7.90	13.5	0.33
	8.05	106.4	2.62	8.00	14.0	0.34
Ave	**7.986**	**106.1**	**2.61**	**7.976**	**13.7**	**0.33**
St Dev	**0.061**	**0.277**	**0.01**	**0.063**	**0.339**	**0.01**

(0.5% fibre)

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Bagasse Red soil	7.99	105.3	2.59	7.95	11.5	0.28
	7.94	99.0	2.44	8.00	13.0	0.32
	8.03	110.4	2.72	7.98	12.1	0.30
	8.01	108.7	2.68	7.98	12.0	0.29
	7.93	98.9	2.44	7.99	12.1	0.30
Ave	**7.98**	**104.46**	**2.57**	**7.98**	**12.14**	**0.30**
St Dev	**0.044**	**5.355**	**0.13**	**0.019**	**0.541**	**0.01**
Bagasse Brown soil	7.97	81.7	2.01	7.98	11.6	0.28
	7.98	82.0	2.02	7.93	11.1	0.27
	7.94	80.5	1.98	8.00	12.4	0.30
	8.02	84.2	2.07	7.98	12.1	0.30
	7.91	80.1	1.97	7.99	12.3	0.30
Ave	**7.964**	**81.7**	**2.01**	**7.976**	**11.9**	**0.29**
St Dev	**0.042**	**1.608**	**0.04**	**0.027**	**0.543**	**0.01**
Coconut	7.94	121.8	3.00	8.02	13.0	0.32
	8.12	123.0	3.03	7.98	11.7	0.29

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Red soil	8.08	122.4	3.01	7.93	11.9	0.29
	7.97	121.9	3.00	8.04	12.9	0.31
	7.97	122.3	3.01	7.97	12.5	0.30
Ave	**8.016**	**122.28**	**3.01**	**7.988**	**12.4**	**0.30**
St Dev	**0.079**	**0.476**	**0.01**	**0.043**	**0.583**	**0.01**
Coconut Brown soil	8.02	109.2	2.69	7.94	11.6	0.28
	8.00	109.5	2.70	8.05	12.5	0.30
	7.93	107.3	2.64	7.97	11.7	0.29
	7.92	108.0	2.66	8.10	11.9	0.29
	8.01	108.1	2.66	8.02	12.0	0.29
Ave	**7.976**	**108.42**	**2.67**	**8.016**	**11.94**	**0.29**
St Dev	**0.047**	**0.909**	**0.02**	**0.063**	**0.351**	**0.01**
Oil Palm Red soil	8.01	116.0	2.86	7.96	13.5	0.33
	7.94	115.7	2.85	8.04	14.2	0.35
	7.92	115.0	2.83	8.00	13.9	0.34
	7.95	114.8	2.83	7.95	13.2	0.32
	8.01	116.1	2.86	7.94	12.8	0.31
Ave	**7.966**	**115.52**	**2.85**	**7.978**	**13.52**	**0.33**
St Dev	**0.042**	**0.589**	**0.01**	**0.041**	**0.554**	**0.01**
Oil Palm Brown soil	7.94	92.4	2.28	7.91	12.6	0.31
	7.91	92.0	2.27	7.93	13.2	0.32
	8.03	93.4	2.30	7.95	12.6	0.31
	7.98	92.9	2.29	8.00	13.8	0.34
	7.90	93.0	2.29	7.99	13.0	0.32
Ave	**7.952**	**92.74**	**2.28**	**7.956**	**13.04**	**0.32**
St Dev	**0.054**	**0.546**	**0.01**	**0.038**	**0.498**	**0.01**

(0.75% fibre)

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Bagasse Red soil	7.92	74.6	1.84	7.94	12.3	0.30
	7.90	73.9	1.82	7.89	11.0	0.27
	7.96	75.1	1.85	7.91	11.8	0.29
	7.94	74.0	1.82	7.93	12.4	0.30
	7.95	74.7	1.84	7.90	12.0	0.29
Ave	**7.934**	**74.5**	**1.83**	**7.914**	**11.9**	**0.29**
St Dev	**0.024**	**0.503**	**0.01**	**0.021**	**0.557**	**0.01**
Bagasse Brown soil	7.91	55.8	1.37	7.91	10.9	0.27
	7.96	57.4	1.41	7.93	11.3	0.28
	7.92	56.6	1.39	7.95	11.8	0.29
	7.94	56.9	1.40	7.92	11.2	0.27
	7.91	55.9	1.38	7.89	10.4	0.25

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Ave	**7.928**	**56.52**	**1.39**	**7.92**	**11.12**	**0.27**
St Dev	**0.022**	**0.676**	**0.02**	**0.022**	**0.517**	**0.01**
Coconut Red soil	7.90	93.7	2.31	7.89	12.6	0.31
	7.95	96.2	2.37	7.94	13.0	0.32
	7.94	95.1	2.34	7.93	12.8	0.31
	7.96	96.6	2.38	7.9	12.2	0.30
	7.92	94.2	2.32	7.91	12.4	0.30
Ave	**7.93**	**95.16**	**2.34**	**7.914**	**12.6**	**0.31**
St Dev	**0.024**	**1.246**	**0.03**	**0.021**	**0.316**	**0.01**
Coconut Brown soil	7.95	72.4	1.78	7.91	11.5	0.28
	7.89	70.5	1.74	7.96	12.7	0.31
	7.90	71.8	1.77	7.93	11.9	0.29
	7.93	71.1	1.75	7.95	12.5	0.30
	7.92	70.9	1.75	7.92	11.9	0.29
Ave	**7.918**	**71.34**	**1.76**	**7.934**	**12.10**	**0.30**
St Dev	**0.024**	**0.757**	**0.02**	**0.021**	**0.490**	**0.01**
Oil Palm Red soil	7.94	86.7	2.14	7.92	12.5	0.30
	7.90	84.9	2.09	7.95	13.2	0.32
	7.93	85.0	2.09	7.91	12.9	0.31
	7.94	86.3	2.13	7.88	12.2	0.30
	7.92	85.6	2.11	7.84	11.8	0.29
Ave	**7.926**	**85.70**	**2.11**	**7.9**	**12.52**	**0.31**
St Dev	**0.017**	**0.791**	**0.02**	**0.042**	**0.554**	**0.01**
Oil Palm Brown soil	7.92	62.4	1.54	7.90	11.6	0.28
	7.95	63.5	1.56	7.89	10.7	0.26
	7.89	61.3	1.51	7.92	11.8	0.29
	7.91	62.7	1.54	7.91	11.6	0.28
	7.94	63.0	1.55	7.90	11.5	0.28
Ave	**7.922**	**62.58**	**1.54**	**7.90**	**11.44**	**0.28**
St Dev	**0.024**	**0.823**	**0.02**	**0.011**	**0.428**	**0.01**

(1% fibre)

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Bagasse Red soil	7.881	63.3	1.56	7.86	11.9	0.29
	7.862	62.5	1.54	7.798	10.8	0.26
	7.901	64.3	1.58	7.842	11.7	0.29
	7.860	63.4	1.56	7.871	12	0.29
	7.896	64.0	1.58	7.850	11.8	0.29
Ave	**7.880**	**63.5**	**1.56**	**7.844**	**11.6**	**0.28**
St Dev	**0.019**	**0.696**	**0.017**	**0.028**	**0.483**	**0.012**
Bagasse	7.817	43.2	1.06	7.852	10.8	0.26

Fibre/Soil Type	Compressive strength			Tensile strength		
	Weight (kg)	Force (KN)	Stress (N/mm^2)	Weight (kg)	Force (KN)	Stress (N/mm^2)
Brown soil	7.870	47.4	1.17	7.86	11.7	0.29
	7.842	45.9	1.13	7.841	10.5	0.26
	7.851	46.2	1.14	7.823	9.8	0.24
	7.830	44.3	1.09	7.81	9.4	0.23
Ave	**7.842**	**45.4**	**1.12**	**7.837**	**10.4**	**0.25**
St Dev	**0.020**	**1.654**	**0.041**	**0.021**	**0.896**	**0.022**
Coconut Red soil	7.870	74.2	1.83	7.838	11.4	0.28
	7.821	71.8	1.77	7.852	12.3	0.30
	7.840	73.4	1.81	7.84	11.8	0.29
	7.839	72.5	1.79	7.819	10.9	0.27
	7.858	75.8	1.87	7.82	11.2	0.27
Ave	**7.858**	**73.5**	**1.81**	**7.834**	**11.5**	**0.28**
St Dev	**0.019**	**1.555**	**0.038**	**0.014**	**0.545**	**0.013**
Coconut Brown soil	7.831	55.3	1.36	7.846	11.5	0.28
	7.822	53.1	1.31	7.802	10.7	0.26
	7.850	56.2	1.38	7.830	11.3	0.28
	7.841	55.7	1.37	7.829	11.0	0.27
	7.850	56.5	1.39	7.817	10.9	0.27
Ave	**7.839**	**55.4**	**1.36**	**7.825**	**11.1**	**0.27**
St Dev	**0.012**	**1.552**	**0.03**	**0.016**	**0.319**	**0.01**
Oil Palm Red soil	7.830	64.1	1.58	7.832	12.3	0.30
	7.861	66.7	1.64	7.824	12.0	0.29
	7.853	66.1	1.63	7.840	12.6	0.31
	7.820	63.4	1.56	7.851	12.9	0.31
	7.844	65.8	1.62	7.822	11.9	0.29
Ave	**7.842**	**65.2**	**1.61**	**7.834**	**12.3**	**0.30**
St Dev	**0.017**	**1.402**	**0.03**	**0.012**	**0.416**	**0.01**
Oil Palm Brown soil	7.816	46.2	1.14	7.810	11.5	0.28
	7.804	45.3	1.12	7.835	12.0	0.29
	7.831	46.8	1.15	7.825	11.8	0.29
	7.820	47.1	1.16	7.831	11.9	0.29
	7.817	46.0	1.13	7.840	12.2	0.30
Ave	**7.818**	**46.3**	**1.14**	**7.828**	**11.9**	**0.29**
St Dev	**0.010**	**0.705**	**0.02**	**0.012**	**0.259**	**0.01**

Appendix I: Durability properties of enhanced soil blocks

(0% fibre)

Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Red Soil	7.722	6.971	10.8	28	41	49	59	0.98
	7.771	7.003	11.0	27	38	47	58	0.97
	7.689	6.854	12.2	30	41	50	62	1.03
	7.613	6.910	10.2	29	40	51	63	1.05
	7.715	6.946	11.1	31	41	52	63	1.05
Ave	**7.702**	**6.937**	**11.0**	**29**	**40.2**	**49.8**	**61**	**1.02**
St Dev	**0.058**	**0.057**	**0.73**	**1.58**	**1.30**	**1.92**	**2.35**	**0.04**
Brown soil	7.528	6.570	14.6	40	84	96	99 @ 54min	1.83
	7.699	6.793	13.3	38	82	95	98 @ 57min	1.56
	7.520	6.601	13.9	39	78	92	97 @ 58min	1.67
	7.533	6.620	13.8	41	83	94	98 @ 56min	1.75
	7.630	6.722	13.5	39	81	93	99 @ 57min	1.74
Ave	**7.582**	**6.661**	**13.8**	**39.4**	**81.6**	**94**	**98.2**	**1.71**
St Dev	**0.079**	**0.093**	**0.48**	**1.14**	**2.30**	**1.58**	**0.84**	**0.10**

(0.25% fibre)

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Bagasse Red soil	7.630	6.950	9.8	27	36	48	56	0.93
	7.657	6.956	10.1	28	37	49	57	0.95
	7.701	6.980	10.3	30	40	50	59	0.98
	7.650	6.987	9.5	29	39	49	58	0.97
	7.700	6.998	10.0	28	40	48	58	0.97
Ave	**7.668**	**6.974**	**9.9**	**28.4**	**38.4**	**48.8**	**57.6**	**0.96**
St Dev	**0.032**	**0.020**	**0.32**	**1.14**	**1.82**	**0.84**	**1.14**	**0.02**
Bagasse Brown soil	7.599	6.793	11.9	34	60	81	92	1.53
	7.670	6.845	12.1	36	62	82	92	1.53
	7.658	6.874	11.4	33	58	78	89	1.48
	7.643	6.88	11.1	35	60	82	91	1.52
	7.667	6.876	11.5	34	61	80	90	1.50
Ave	**7.647**	**6.854**	**11.6**	**34.4**	**60.2**	**80.6**	**90.8**	**1.51**

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
St Dev	**0.029**	**0.037**	**0.38**	**1.14**	**1.48**	**1.67**	**1.30**	**0.02**
Coconut Red soil	7.651	6.977	9.7	26	35	46	55	0.92
	7.614	6.938	9.7	23	33	45	53	0.88
	7.623	6.947	9.7	25	34	47	54	0.90
	7.591	6.984	8.7	26	36	47	56	0.93
	7.597	6.987	8.7	27	36	48	57	0.95
Ave	**7.615**	**6.967**	**9.3**	**25.4**	**34.8**	**46.6**	**55**	**0.92**
St Dev	**0.024**	**0.023**	**0.55**	**1.52**	**1.30**	**1.14**	**1.58**	**0.03**
Coconut Brown soil	7.667	6.877	11.5	31	51	70	81	1.35
	7.640	6.903	10.7	30	50	71	82	1.37
	7.580	6.879	10.2	32	50	72	82	1.37
	7.612	6.864	10.9	29	49	69	79	1.32
	7.603	6.901	10.2	31	50	70	80	1.33
Ave	**7.620**	**6.885**	**10.7**	**30.6**	**50**	**70.4**	**80.8**	**1.35**
St Dev	**0.034**	**0.017**	**0.55**	**1.14**	**0.71**	**1.14**	**1.30**	**0.02**
Oil Palm Red soil	7.703	6.992	10.2	28	37	47	55	0.92
	7.682	6.987	9.9	30	36	46	55	0.92
	7.691	6.899	11.5	29	39	48	56	0.93
	7.690	6.940	10.8	28	37	48	56	0.93
	7.713	6.970	10.7	29	38	49	57	0.95
Ave	**7.696**	**6.958**	**10.6**	**28.8**	**37.4**	**47.6**	**55.8**	**0.93**
St Dev	**0.012**	**0.039**	**0.60**	**0.84**	**1.14**	**1.14**	**0.84**	**0.01**
Oil Palm Brown soil	7.640	6.885	11.0	35	59	79	87	1.45
	7.682	6.894	11.4	33	57	75	85	1.42
	7.678	6.880	11.6	32	56	76	84	1.40
	7.630	6.879	10.9	34	57	78	85	1.42
	7.612	6.799	12.0	33	55	73	83	1.38
Ave	**7.648**	**6.867**	**11.4**	**33.4**	**56.8**	**76.2**	**84.8**	**1.41**
St Dev	**0.031**	**0.039**	**0.44**	**1.14**	**1.48**	**2.39**	**1.48**	**0.02**

(0.5% fibre)

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Bagasse Red soil	7.572	6.976	8.5	16	27	32	41	0.68
	7.563	6.98	8.4	18	28	35	42	0.70
	7.530	6.894	9.2	19	30	35	44	0.73
	7.616	7.023	8.4	17	27	33	40	0.67
	7.640	7.007	9.0	20	31	36	43	0.72
Ave	**7.584**	**6.976**	**8.7**	**18**	**28.6**	**34.2**	**42**	**0.70**
St Dev	**0.044**	**0.050**	**0.39**	**1.58**	**1.82**	**1.64**	**1.58**	**0.03**

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Bagasse Brown soil	7.613	6.87	10.8	27	46	62	78	1.30
	7.564	6.986	8.3	25	45	60	75	1.25
	7.603	6.974	9.0	28	48	64	79	1.32
	7.576	6.897	9.8	26	47	61	76	1.27
	7.562	6.89	9.8	27	46	63	77	1.28
Ave	**7.584**	**6.923**	**9.5**	**26.6**	**46.4**	**62**	**77**	**1.28**
St Dev	**0.023**	**0.053**	**0.95**	**1.14**	**1.14**	**1.58**	**1.58**	**0.03**
Coconut Red soil	7.600	7.046	7.9	15	24	32	39	0.65
	7.512	7.012	7.1	17	25	34	40	0.67
	7.604	6.98	8.9	18	28	35	41	0.68
	7.524	6.97	7.9	15	25	33	38	0.63
	7.547	6.983	8.1	16	25	33	39	0.65
Ave	**7.557**	**6.998**	**8.0**	**16.2**	**25.4**	**33.4**	**39.4**	**0.66**
St Dev	**0.043**	**0.031**	**0.65**	**1.30**	**1.52**	**1.14**	**1.14**	**0.02**
Coconut Brown soil	7.573	6.930	9.3	25	44	58	73	1.22
	7.505	6.876	9.1	23	43	57	70	1.17
	7.543	6.960	8.4	24	45	59	71	1.18
	7.600	6.940	9.5	24	44	57	72	1.20
	7.543	6.870	9.8	25	46	58	72	1.20
Ave	**7.553**	**6.915**	**9.2**	**24.2**	**44.4**	**57.8**	**71.6**	**1.19**
St Dev	**0.036**	**0.040**	**0.53**	**0.84**	**1.14**	**0.84**	**1.14**	**0.02**
Oil Palm Red soil	7.660	7.050	8.7	17	26	35	40	0.67
	7.642	6.976	9.5	18	27	36	42	0.70
	7.658	7.030	8.9	16	26	33	41	0.68
	7.675	7.012	9.5	15	25	34	41	0.68
	7.638	6.980	9.4	17	27	35	40	0.67
Ave	**7.655**	**7.010**	**9.2**	**16.6**	**26.2**	**34.6**	**40.8**	**0.68**
St Dev	**0.015**	**0.032**	**0.39**	**1.14**	**0.84**	**1.14**	**0.84**	**0.01**
Oil Palm Brown soil	7.574	6.902	9.7	26	45	59	75	1.25
	7.590	6.915	9.8	24	44	58	73	1.22
	7.610	6.952	9.5	25	46	60	75	1.25
	7.606	6.957	9.3	25	45	58	76	1.27
	7.634	6.960	9.7	26	47	59	77	1.28
Ave	**7.603**	**6.937**	**9.6**	**25.2**	**45.4**	**58.8**	**75.2**	**1.25**
St Dev	**0.023**	**0.027**	**0.19**	**0.84**	**1.14**	**0.84**	**1.48**	**0.02**

(0.75% fibre)

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Bagasse	7.642	7.021	8.8	15	24	31	40	0.67
	7.590	7.054	7.6	17	25	34	42	0.70

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Red soil	7.624	6.990	9.1	14	26	33	39	0.65
	7.597	7.029	8.1	16	24	30	41	0.68
	7.606	7.030	8.2	17	26	32	42	0.70
Ave	**7.612**	**7.025**	**8.4**	**15.8**	**25**	**32**	**40.8**	**0.68**
St Dev	**0.021**	**0.023**	**0.60**	**1.30**	**1.00**	**1.58**	**1.30**	**0.02**
Bagasse Brown soil	7.598	6.938	9.5	23	43	59	72	1.20
	7.608	6.923	9.9	26	45	62	75	1.25
	7.615	6.970	9.3	25	46	60	73	1.22
	7.589	6.978	8.8	25	44	62	74	1.23
	7.597	6.947	9.4	24	42	60	72	1.20
Ave	**7.601**	**6.951**	**9.4**	**24.6**	**44**	**60.6**	**73.2**	**1.22**
St Dev	**0.010**	**0.023**	**0.41**	**1.14**	**1.58**	**1.34**	**1.30**	**0.02**
Coconut Red soil	7.618	7.027	8.4	14	22	33	38	0.63
	7.564	7.046	7.4	12	21	30	35	0.58
	7.584	7.050	7.6	13	20	31	36	0.60
	7.604	6.990	8.8	14	23	32	37	0.62
	7.592	7.063	7.5	13	22	32	35	0.58
Ave	**7.592**	**7.035**	**7.9**	**13.2**	**21.6**	**31.6**	**36.2**	**0.60**
St Dev	**0.020**	**0.028**	**0.64**	**0.84**	**1.14**	**1.14**	**1.30**	**0.02**
Coconut Brown soil	7.613	6.963	9.3	21	39	52	67	1.12
	7.574	6.942	9.1	24	42	55	70	1.17
	7.582	6.939	9.3	22	40	54	68	1.13
	7.589	6.940	9.4	23	43	55	69	1.15
	7.605	6.960	9.3	22	41	53	67	1.12
Ave	**7.593**	**6.949**	**9.3**	**22.4**	**41**	**53.8**	**68.2**	**1.14**
St Dev	**0.016**	**0.012**	**0.10**	**1.14**	**1.58**	**1.30**	**1.30**	**0.02**
Oil Palm Red soil	7.598	6.95	9.3	13	22	30	37	0.62
	7.589	6.936	9.4	14	25	32	39	0.65
	7.608	6.957	9.4	14	24	33	40	0.67
	7.592	6.952	9.2	13	21	31	38	0.63
	7.617	6.960	9.4	15	25	32	40	0.67
Ave	**7.601**	**6.951**	**9.3**	**13.8**	**23.4**	**31.6**	**38.8**	**0.65**
St Dev	**0.012**	**0.009**	**0.09**	**0.84**	**1.82**	**1.14**	**1.30**	**0.02**
Oil Palm Brown soil	7.556	6.897	9.6	24	43	58	73	1.22
	7.581	6.934	9.3	22	40	55	70	1.17
	7.578	6.922	9.5	23	42	56	71	1.18
	7.580	6.937	9.3	22	41	56	72	1.20
	7.567	6.931	9.2	24	42	57	72	1.20
Ave	**7.572**	**6.924**	**9.4**	**23**	**41.6**	**56.4**	**71.6**	**1.19**
St Dev	**0.011**	**0.016**	**0.15**	**1.00**	**1.14**	**1.14**	**1.14**	**0.02**

(1% fibre)

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	Final Weight (kg)	Reduction (%)	15min (mm)	30min (mm)	45min (mm)	60min (mm)	Erosion Rate (mm/min)
Bagasse Red soil	7.568	7.001	8.1	16	25	32	42	0.70
	7.571	6.987	8.4	19	28	36	44	0.73
	7.540	6.966	8.2	17	27	35	43	0.72
	7.573	7.002	8.2	19	28	36	44	0.73
	7.580	6.990	8.4	18	27	35	43	0.72
Ave	**7.566**	**6.989**	**8.3**	**17.8**	**27**	**34.8**	**43.2**	**0.72**
St Dev	**0.015**	**0.015**	**0.14**	**1.30**	**1.22**	**1.64**	**0.84**	**0.01**
Bagasse Brown soil	7.542	6.896	9.4	27	47	63	76	1.27
	7.561	6.923	9.2	25	45	61	75	1.25
	7.550	6.897	9.5	26	46	62	75	1.25
	7.528	6.868	9.6	27	47	63	76	1.27
	7.490	6.849	9.4	26	46	62	75	1.25
Ave	**7.534**	**6.887**	**9.4**	**26.2**	**46.2**	**62.2**	**75.4**	**1.26**
St Dev	**0.027**	**0.029**	**0.15**	**0.84**	**0.84**	**0.84**	**0.55**	**0.01**
Coconut Red soil	7.568	7.019	7.8	16	25	35	41	0.68
	7.490	6.950	7.8	15	23	34	39	0.65
	7.546	6.990	8.0	14	22	33	38	0.63
	7.581	7.012	8.1	16	25	35	40	0.67
	7.570	6.998	8.2	15	24	34	40	0.67
Ave	**7.551**	**6.994**	**8.0**	**15.2**	**23.8**	**34.2**	**39.6**	**0.66**
St Dev	**0.036**	**0.027**	**0.18**	**0.84**	**1.30**	**0.84**	**1.14**	**0.02**
Coconut Brown soil	7.432	6.83	8.8	25	44	56	71	1.18
	7.544	6.889	9.5	25	43	55	70	1.17
	7.470	6.800	9.9	24	44	54	69	1.15
	7.461	6.890	8.3	24	44	55	70	1.17
	7.387	6.771	9.1	25	44	56	71	1.18
Ave	**7.459**	**6.836**	**9.1**	**24.6**	**43.8**	**55.2**	**70.2**	**1.17**
St Dev	**0.058**	**0.053**	**0.61**	**0.55**	**0.45**	**0.84**	**0.84**	**0.01**
Oil Palm Red soil	7.564	6.878	10.0	16	26	34	42	0.70
	7.540	6.890	9.4	15	24	33	40	0.67
	7.537	6.897	9.3	15	25	33	41	0.68
	7.529	6.892	9.2	16	26	34	43	0.72
	7.550	6.879	9.8	14	25	33	40	0.67
Ave	**7.544**	**6.887**	**9.5**	**15.2**	**25.2**	**33.4**	**41.2**	**0.69**
St Dev	**0.013**	**0.008**	**0.32**	**0.84**	**0.84**	**0.55**	**1.30**	**0.02**
Oil Palm Brown	7.345	6.709	9.5	25	45	59	76	1.27
	7.387	6.766	9.2	24	42	57	74	1.23
	7.350	6.695	9.8	25	43	58	74	1.23
	7.298	6.640	9.9	25	44	58	75	1.25

Fibre/ Soil Type	Wearing			Erosion				
	Initial Weight (kg)	**Final Weight (kg)**	**Reduction (%)**	**15min (mm)**	**30min (mm)**	**45min (mm)**	**60min (mm)**	**Erosion Rate (mm/min)**
soil	7.360	6.690	10.0	23	43	57	73	1.22
Ave	**7.348**	**6.700**	**9.7**	**24.4**	**43.4**	**57.8**	**74.4**	**1.24**
St Dev	**0.032**	**0.045**	**0.34**	**0.89**	**1.14**	**0.84**	**1.14**	**0.02**

Appendix J: Gaps between fibres and soil matrix

Sample	Gap (mm)		
	Bagasse	Coconut	Oil Palm
1	0.031	0.053	0.050
2	0.020	0.060	0.031
3	0.014	0.051	0.033
4	0.012	0.083	0.031
5	0.031	0.054	0.030
6	0.027	0.114	0.039
7	0.013	0.062	0.041
8	0.012	0.051	0.038
9	0.008	0.063	0.045
10	0.025	0.083	0.034
11	0.009	0.118	0.036
12	0.014	0.074	0.042
13	0.030	0.109	0.034
14	0.028	0.085	0.042
15	0.010	0.066	0.041
16	0.029	0.084	0.037
17	0.008	0.072	0.032
18	0.011	0.106	0.048
19	0.009	0.093	0.036
20	0.025	0.061	0.040
Ave	**0.018**	**0.077**	**0.038**
Std Dev	**0.009**	**0.022**	**0.006**

Appendix K: Dry, saturated and shrinkage of fibres

Sample	Coconut (mm)			Bagasse (mm)			Oil Palm (mm)		
	Dry diameter (mm)	Wet diameter (mm)	Shrinkage (mm)	Dry diameter (mm)	Wet diameter(mm)	Shrinkage (mm)	Dry diameter (mm)	Wet diameter(mm)	Shrinkage (mm)
1	0.3	0.38	0.08	0.48	0.49	0.01	0.16	0.21	0.05
2	0.39	0.47	0.08	0.77	0.79	0.02	0.26	0.3	0.04
3	0.4	0.49	0.09	0.63	0.64	0.01	0.28	0.33	0.05
4	0.36	0.44	0.08	0.97	1	0.03	0.17	0.21	0.04
5	0.39	0.47	0.08	0.53	0.56	0.03	0.46	0.52	0.06
6	0.38	0.44	0.06	0.49	0.51	0.02	0.48	0.54	0.06
7	0.35	0.44	0.09	0.75	0.77	0.02	0.33	0.38	0.05
8	0.34	0.47	0.13	0.76	0.78	0.02	0.51	0.56	0.05
9	0.27	0.33	0.06	0.61	0.62	0.01	0.57	0.62	0.05
10	0.32	0.38	0.06	0.51	0.54	0.03	0.34	0.39	0.05
11	0.9	1.01	0.11	0.96	1. 00	0.04	0.56	0.63	0.07
12	1.00	1.15	0.15	0.79	0.82	0.03	0.51	0.56	0.05
13	0.68	0.79	0.11	1.11	1.15	0.04	0.44	0.49	0.05
14	0.64	0.74	0.1	0.93	0.97	0.04	0.38	0.43	0.05
15	0.78	0.86	0.08	0.74	0.76	0.02	0.3	0.34	0.04
16	0.65	0.77	0.12	0.91	0.93	0.02	0.29	0.34	0.05
17	0.6	0.69	0.09	1.22	1.25	0.03	0.27	0.33	0.06
18	0.7	0.81	0.11	0.82	0.85	0.03	0.26	0.31	0.05
19	0.57	0.66	0.09	0.68	0.71	0.03	0.24	0.29	0.05
20	0.56	0.66	0.1	0.72	0.74	0.02	0.23	0.27	0.04
Ave	**0.529**	**0.623**	**0.094**	**0.769**	**0.794**	**0.025**	**0.352**	**0.403**	**0.051**
Std Dev	**0.211**	**0.227**	**0.023**	**0.204**	**0.209**	**0.009**	**0.128**	**0.132**	**0.008**

Appendix L: Technical guide for production of agricultural waste fibre reinforced soil blocks

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Table of Content

Benefits of agricultural waste fibre reinforced soil blocks

Technical

- Good resistance against crack
- Good resistance against erosion
- Good resistance against wearing
- Good resistance against shrinkage
- Good resistance against collapse

Economic

- Soil and fibres are abundant and cheap
- Cost of preparation is low
- It can be used to build low-cost housing
- Cost of maintenance is low
- Does not require transportation cost

Environmental

- Reduction of pollution from burning waste residue
- Produce cool room temperature
- Reduction of CO_2 emission
- It can be reused

Social

- It is easy to transfer skill for making and using the blocks
- It is easy to incorporate cultural patterns and symbols in the design
- It promotes cultural heritage and natural setting
- It promotes self-help construction advantages

Preparation of agricultural waste residue

Source: agricultural waste residue can be obtained at stage of disposal as a by-product from home, both small and large scale industries and street vendors.

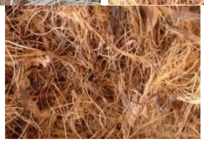

Sugarcane residue Coconut husk

Weathering: the residue should be kept in water for 1 day to weaken the pith particles that hold the fibres together.

Beating: after weathering, use a wooden rod of about 60mm diameter and 300mm length to beat the residue on any hard surface to separate the fibres from the pith particle. Some residue such as sugarcane should first be cut at the nodes before being beaten.

Separation: use your hands to separate the fibres from the pith particles. Wash the fibres in water to remove any unwanted materials and dry in the sun or open air for 2 weeks





Sugarcane fibre Coconut fibre Oil palm fibre

Preparation of soil

Source: soil for making blocks can be obtained at any site which is not only clay or rock. The site should be cleared of weeds, trees and stumps. The top soil (up to 300mm) should be removed because it contains organic matter. The soil beneath can be dug for making blocks.

Dug soil

Sieving: any unwanted materials (tree roots, bigger stone, pieces of metals etc.) should be removed from the soil. Sieve the soil through metal mesh of 20mm size.

Drying: spread the soil in the sun to dry for 2 weeks. Turn the soil every two days to ensure even drying.

Mixing of the soil and fibres

Batching: use weighing scale to measure 0.5% weight of fibre to soil. Keep the fibre in water for one day before use to prevent quick absorption of water in the soil-fibre mixture.

Mixing: weigh and spread soil on platform. Add the measured and saturated fibre and mix for the fibre to evenly mix with the soil. Weigh 20% water to soil and gradually sprinkle on the

soil-fibre mixture and turn till uniform paste is obtained. The mixture is ready to use.

Moulding of blocks

Press machine: set up and wet the mould of the hand press block making machine.

Make blocks: determine the required quantity of the mixture for making one block and use it to fill the mould box. Place the top cover of the mould box on the mould and press the handle to compress the mixture. Release the top cover and push the block up.

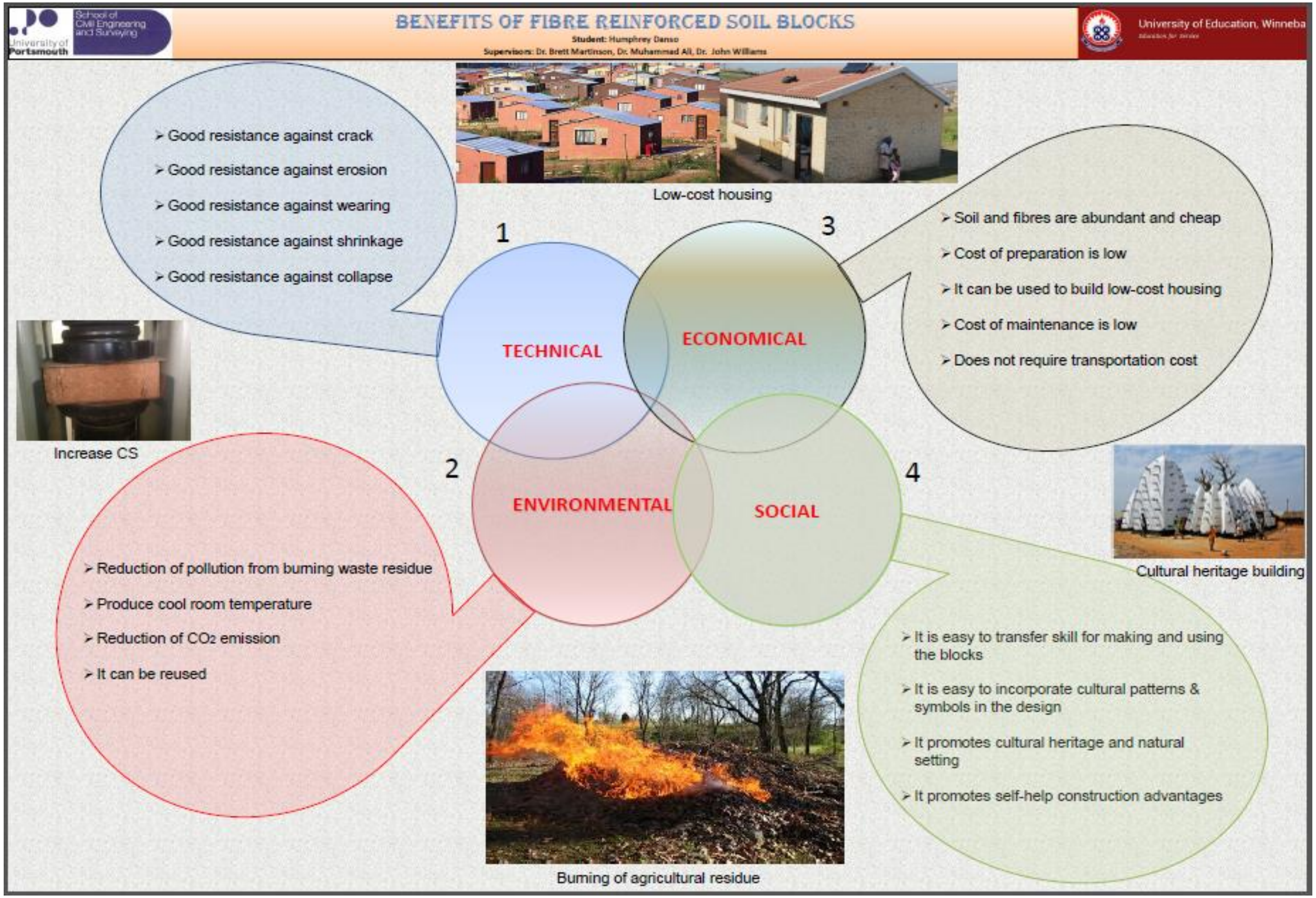
Moulding blocks

Drying of the blocks

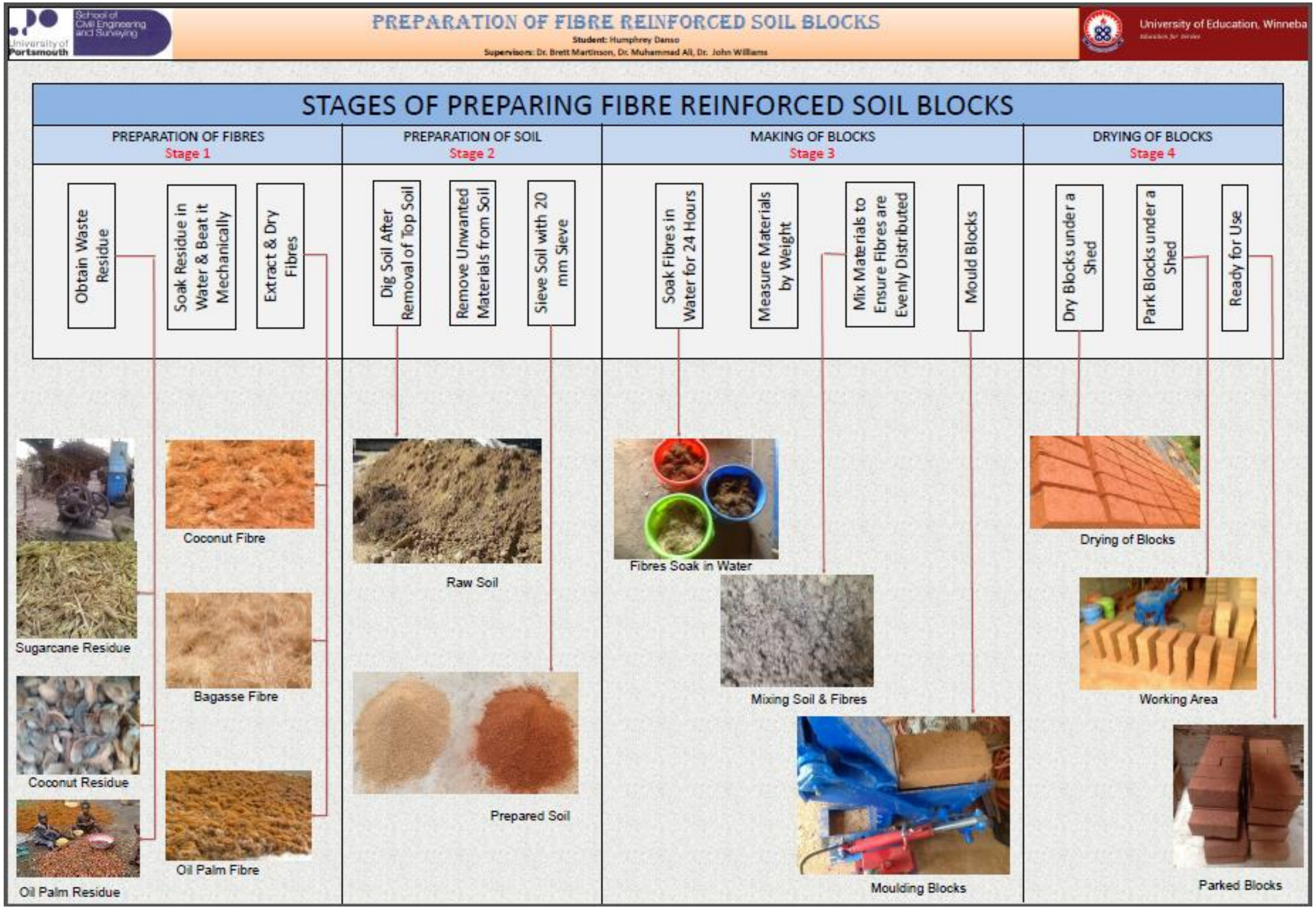
Remove the block from the press machine and send to the drying area to dry for 21 days. Make sure the drying area has shed to prevent rain from destroying the freshly made blocks.


Drying blocks

Appendix M: Poster on the benefits of agricultural waste fibre reinforced soil blocks



Appendix N: Poster on the production of agricultural waste fibre reinforced soil blocks



Appendix O: Production of agricultural waste fibre reinforced soil blocks workshop feedback form

We welcome and value your opinion about the agricultural waste reinforced soil blocks. The feedback process is anonymous. Please tick [**√**] your opinion (strongly disagree - strongly agree) on the statements below.

s/n	Statement	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
1	I find the fibre reinforced soil blocks useful for building houses					
2	I intend to use fibre reinforced soil blocks in future					
3	Using fibre reinforced soil blocks will help to produce durable houses					
4	Using fibre reinforced soil blocks will help to produce cool room temperature houses					
5	Using fibre reinforced soil blocks will help to reduce pollution of the environment					
6	Producing fibre reinforced soil blocks will be easy					
7	Resources require for producing fibre reinforced soil blocks are available					
8	Fibre reinforced soil blocks will be affordable					
9	Fibre reinforced soil blocks can be used to produce low-cost housing					
10	Fibre reinforced soil blocks can be used to address inadequate housing problem					
11	The delivery of the workshop was satisfactory					
12	The resources provided for the workshop were helpful					
13	I am satisfied with the general organisation of the workshop					

Please add any suggestion(s) or recommendation(s) for improvement:

Thank you for taking the time to submit your feedback.

If this form is not collected at the end of the workshop, please return to: Humphrey Danso, Department of Construction & Wood Technology, University of Education Winneba-Kumasi Campus, P.O. Box 1277, Kumasi.

FORM UPR16

Research Ethics Review Checklist

Please include this completed form as an appendix to your thesis (see the Postgraduate Research Student Handbook for more information

University of Portsmouth

Postgraduate Research Student (PGRS) Information		**Student ID:**	676877
PGRS Name:	HUMPHREY DANSO		
Department:	SCES	**First Supervisor:**	DR. BRETT MARTINSON
Start Date: (or progression date for Prof Doc students)		01/02/2013	

Study Mode and Route:	Part-time ☐	MPhil ☐	MD ☐
	Full-time ☒	PhD ☒	Professional Doctorate ☐

Title of Thesis:	USE OF AGRICULTURAL WASTE FIBRES AS ENHANCEMENT OF SOIL BLOCKS FOR LOW-COST HOUSING IN GHANA
Thesis Word Count: (excluding ancillary data)	50,775

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist: (If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)	
a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:	
I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)	
Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	B017-AEA4-9239-DE69-7977-46D0-474F-A2CA
If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of questions a) to e), please explain below why this is so:	

Signed *(PGRS)*:		**Date:** 28/10/2015